DESIGN OF A PRESSURE SENSITIVE CELL
AND
MODEL STUDIES OF PRESSURES IN THE SUBGRADE OF A FLEXIBLE PAVEMENT SYSTEM

NOVEMBER 1959

NO. 24

Joint
Highway
Research
Project

by

T. F. McMAHON

PURDUE UNIVERSITY
LAFAYETTE INDIANA

Final Report

DESIGN OF A PRESSURE SENSITIVE CELL

AND

MODEL STUDIES OF PRESSURES IN THE SUBGRADE OF A FLEXIBLE PAVEMENT SYSTEM

TO: K. B. Woods, Director
Joint Highway Research Project
November 19, 1959

FROM: H. L. Michael, Assistant Director
Joint Highway Research Project
File: 6-20-4
Project: C-36-52D

Attached is a final report entitled "Design of a Pressure Sensitive Cell and Model Studies of Pressures in the Subgrade of a Flexible Pavement System" by T. F. McMahon, graduate assistant on our staff. The research reported was performed under the direction of Professor E. J. Yoder and was also used by Mr. McMahon as his thesis requirement for the PhD Degree.

This report presents the design and development of a pressure sensitive cell and the use of this cell in making pressure measurements in homogeneous and two-layer model pavement systems.

The report is presented for the record.

Respectfully submitted,

H. L. Michael

H. L. Michael, Secretary

HLM:pg

Attachment

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C. E. Vogelgesang
J. L. Waling
J. E. Wilson
E. J. Yoder

Final Report

DESIGN OF A PRESSURE SENSITIVE CELL
AND
MODEL STUDIES OF PRESSURES IN THE SUBGRADE OF A FLEXIBLE PAVEMENT SYSTEM

By

Thurmul Francis McMahon
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Joint Highway Research Project
Project No: C-36-52D
File No: 6-20-4

Purdue University
Lafayette, Indiana

August 1959

ACKNOWLEDGMENTS

The writer wishes to express his appreciation to Professor K. B. Woods, Head of the School of Civil Engineering, Purdue University; to Mr. C. E. Vogelgesang, Engineer of Highways, Indiana State Highway Commission; and to the members of the Joint Highway Research Project, Purdue University, who have made this study possible.

Special acknowledgement is made to Professor E. J. Yoder, the writer's major professor and supervisor of the project, for his guidance and encouragement throughout the project, and to Professor G. A. Leonards, Head of the Department of Soil Mechanics, for his generous assistance and helpful suggestions in carrying on this investigation.

Appreciative acknowledgment is made to Professor E. C. Stitz, Division of Engineering Sciences, for his assistance and helpful suggestions in the development of the pressure cell and to Professor A. D. M. Lewis, School of Civil Engineering, for his assistance in the instrumentation of the project.

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ABSTRACT

Mc Mahon, Thurmul Francis. Ph. D., Purdue University, August, 1959. "Design of a Pressure Sensitive Cell and Model Studies of Pressures in the Subgrade of a Flexible Pavement System." Major Professor: Eldon J. Yoder.

This thesis reports the design and development of a pressure sensitive cell and the use of this cell in making pressure measurements in homogeneous and two-layer model pavement systems.

The pressure cell is of the diaphram type, one and one-half inches in diameter and three eighths of an inch thick. SR-4 Strain Gages are used to measure the deflection of the diaphram as pressure is applied to the cell. A study was made of the action of the cell in clay-soil and in sand media, as compared to its performance during calibration under air pressure. It was determined that the performance in the clay-soil was very similar to that in air, but that in sand the cell behavior was erratic.

Pressures were measured under three different size plates, on a homogeneous compacted clay fill, and on the same fill when varying thicknesses of the upper portion of the clay had been replaced with a compacted crushed limestone base. These measured pressures have been compared with the theoretical pressures, as determined by the Boussinesq and the Burmister Methods. They have also been compared with pressure measurements made by the Corps of Engineers, at their Waterways Experiment Station. A fair correlation of measured and

theoretical pressures has been made by using a modification of the Boussinesq method, called the Equivalent Plate Method. However, it is necessary to have the magnitude of the interface pressure to establish this correlation.

The following are some of the conclusions that have been made during this study:

1. The pressure cell, which was designed and developed as part of the project, measured the pressures within the subgrade with an accuracy which should make it a very helpful tool in furthering knowledge of pressure distributions.

2. The stress distribution within a homogeneous soil mass, under a semi-rigid plate, is similar to the Boussinesq pattern of distribution for a uniformly loaded area.

3. The stress distribution within a homogeneous soil mass is affected but very little by a considerable change in strength of the mass.

4. The stress distribution in a two-layer system depends to a large extent upon the strength and thickness of the upper layer.

INTRODUCTION

Although flexible pavements have been constructed for hundreds of years, the design of such pavements is still based on empirical methods. Pavement thicknesses are still determined through personal experience, by service characteristics, or by empirical formulas which correlate service records with measurable qualities of pavements and subgrades.

These methods have proven satisfactory where performance data and pavement and subgrade qualities are well correlated. However, in areas where correlation is inadequate, or where load and use characteristics must be changed, these methods are of little value. Thus, it is apparent that some rational means of pavement design must be formulated, in order that a more economical use may be made of our natural resources, and a better pavement performance insured.

Webster defines the word rational as: "having reason or understanding." Hence, before a rational method of design can be established, it is necessary that the function of a pavement be fully understood.

In the design of any structure, on a rational basis, it is necessary that the applied forces, the stress distributions, and the physical properties of the materials be known and understood. In highway design the total applied load, the tire pressures, and the contact areas are usually known. The load distribution over the tire contact area has been studied by the Civil Aeronautics Administration (2) and

the Bureau of Public Roads. (41) If this distribution is found to be of importance in a rational method of design, it should be possible to establish values for tire sizes, tire pressures, and gross loads. Recent advances, in soil mechanics and mechanics of materials, enable adequate measurement of the physical properties of paving and subgrade materials for use in a rational method of design if the test conditions were known. The transition from a loaded area to a stress in a given paving material, especially when the system is multi-layered, as are all pavements, is one of the important factors in establishing such a design method.

Ever since Boussinesq (4) presented his classic solution of stress distributions, in 1885, mathematicians and engineers have been applying his solution, or modifications of his solution, to pavement design. It is only in recent years that any attempt has been made to rationalize this method, to some extent, by the use of factors which consider the effects of the various strengths of the materials in the layered system.

Attempts have been made to measure the pressure distribution within the pavement mass, (13) (14) and other investigators are presently concerned with this subject. (13) Most of these projects have been carried out under costly conditions, using large size measuring devices and prototype methods. Also, the greater portion of the investigations have dealt with one-layer systems only.

In the study of stress distributions, it is essential to have an accurate pressure measuring device, or devices, which will be small enough to minimize its effect on the actions of the materials,

but large enough to measure average pressures, rather than localized stresses. A major purpose of this study was to develop such a device.

The Civil Aeronautics Administration (27) and Spangler, of Iowa State College, (39) have measured pressures transferred through pavements to the subgrade with some success. As yet, except for the present large scale project of the Corps of Engineers, (13) no one has undertaken a complete investigation of the distribution of pressures within the subgrade, or the effect of the component parts of the pavement on these pressures.

In order to further the knowledge concerning stress distributions, the pressure measuring device was used in a model study of pressure distributions in a compacted subgrade under several layered systems. The objective of these latter measurements was to contribute to the eventual formulation of a rational method of flexible pavement design.

LITERATURE SURVEY

Pressure Cells

The search of the literature pertaining to pressure cells disclosed many articles on the design and use of the cell. However, it was apparent that factual information on the design of the cell was limited and much research was still needed.

One of the first, and probably the most noted, attempts to measure pressures within soil masses was made by A. T. Goldbeck and E. B. Smith (19). The authors describe an apparatus for measuring pressures under earth fills or against walls. This apparatus consisted of a small cell having a thin annular diaphram. The cell was connected to an air supply by a small pipe and to electrical measurement equipment by lead wires. In order to measure pressures exerted against the cell, air was pumped into the cell until equilibrium was established with the external pressure. Equilibrium was indicated by the breaking of an electrical contact on the inside surface of the diaphram. A gage reading of the air pressure, at the equilibrium condition, indicated the external pressure on the diaphram. This cell, the Goldbeck Cell, is still used in many investigations of earth pressure.

A later paper by Mr. Goldbeck (23) tells of the use of this device in measuring pressures in subgrades under flexible pavement.

Another pioneer in the measurement of pressures in soil masses was R. W. Carlson of the Massachusetts Institute of Technology. His first researches were in the measurement of stresses in concrete (8).

He later adapted his strainmeter to the measurement of soil pressures against rigid walls, in soil masses, and under pavements. The cell operated by transmission of pressure, which acted on a flat, circular face plate, through a confined liquid to a metal diaphram. The deflection of the diaphram actuated a strainmeter consisting of two coiled wire resistances. The resistance changes in the coiled wires, produced by the deflection of the diaphram, were measured by a precise bridge arrangement.

In 1936, W. C. Huntington and E. J. Luetzelschawb of Illinois University (28) described a pressure measuring device which avoided the disadvantages inherent in the movement of the diaphram of the Goldbeck cell. This device consisted of a revolving steel plate between two fixed steel plates faced with Oilite washers. A cable, making several turns around a pulley, activated the revolving wheel. The pull on the cable necessary to cause a uniform rate of rotation of the wheel was measured with a spring balance. This force was an indication of the normal pressure acting against the cell face. The device was capable of calibration for differing use conditions and has been used in several experimental studies at the University of Illinois.

An interesting investigation was reported by M. G. Spangler of Iowa State College (37) in which the pressures against retaining walls were studied. These studies were made by means of a device in which a steel tape was held between two steel plates, one plate being held rigid in the wall and the other being held flush with the wall by the soil. The pull necessary to overcome the friction between the two plates and the tape was a measure of the normal soil pressure on the plates.

Spangler and Ustrud (40) used small carbon disk piles for measuring pressures transmitted through flexible pavement to the subgrade. The change in electrical resistance of the carbon piles, when under pressure, was calibrated and used for the purpose of making these measurements. This research was also done at Iowa State College.

A. C. Benkelman and R. J. Lancaster (3) were among the first to investigate the variables inherent in the use of pressure cells. In their research a study was made of the effects of various cells of differing size and shape. Pressure sensitive areas varied from 1.0 to 5.05 inches in diameter, i.e. from 4.0 to 0.79 in perimeter-area ratios. The study of size effects was held mainly to the effect of the size of the pressure sensitive area and the effect of various rim sections surrounding the sensitive area. This was accomplished by placing the pressure cells face down on a soil and loading them with suitable increments of load. The experiment was first performed using a cell without a rim section, then with cells having various rim widths. The pressures indicated by the cells correlated very poorly with the applied pressure, for the rim type cells. This lack of correlation was attributed to the difficulty of properly seating the cells on the soil.

In order to study the effect of size and thickness of the cells on the readings obtained, Benkelman and Lancaster embedded pressure cells of varying size and thickness in the bottom of a box. The box was then filled with a different type of soil for each of a series of tests. Loads were applied to the soil with a concrete block that covered the soil surface. This method of loading introduced boundary conditions very unlike those to be encountered in the field but sufficed for this experiment. When the cells were installed flush with

the base, differences of -3 percent to ≠18 percent of the applied stress existed in the pressures indicated by the various cells. Relationships could not be developed for the direct comparison of the several individual cells. However, it was noted that the differences were greatest between cells of different size and that these differences were much less when the soils used were plastic rather than granular. A series of tests to evaluate the effect of cell thickness was performed by changing the amount of protrusion of the cells into the soil from the bottom of the box. In the clay soil a difference was noted, with the varying amounts of protrusion of the cells and various rim thicknesses, of values 0 percent to 5 percent above the applied stress.

Benkelman and Lancaster concluded that for dry sand, and dry or moist loam, the physical dimensions of the cell, as measured by the thickness and by the perimeter-area ratio, are directly related to the ratio of the measured stress to the applied stress. In the case of plastic clays, however, the physical dimensions of the cell seemed to have less effect on the accuracy of the pressure indications. The measured stress was in almost all cases within 5 percent of the applied stress.

The Waterways Experiment Station of the Corps of Engineers has also investigated the soil pressure cell and limitations of its use (10). In this investigation it was determined that the thickness of the cell and compressibility of the diaphram must be held within certain limits in order to obtain valid pressure indications. In a sand medium, the ratio of cell diameter to the amount of projection

from a rigid surface should be greater than thirty in order to obtain readings comparable to those for flush mounted cells. A cell placed near the center of a sand mass will indicate pressures relative to the pressure applied at the surface, if the cell has a diameter-thickness ratio of greater than five. A cell diameter-diaphram deflection ratio of greater than two thousand is needed to obtain comparable readings between cells.

A later publication of the Waterways Experiment Station, Pressure Cells for Field Use, (11) discusses numerous types of cells as to their design and capabilities. These cells were of a type where motion of a diaphram is changed to electrical impulses that are measured by electronic equipment. Important features of the design of pressure cells were pointed out in this article. Basically the design of a pressure cell is governed by the type and magnitude of the pressure, the materials available, and the limitations of fabrication. The cells must be rugged and durable, with stable characteristics which will enable the use of calibration constants over long periods of time. The materials used in the construction of the cell must also be compatible with the expected stresses and the sensitivity desired. The sensitivity can be controlled in design, but the relationship of size and deflection should be maintained.

The Waterways Experiment Station pressure cell is nominally six inches in diameter and one inch in overall thickness. It consists of a circular face plate welded at its perimeter to a thicker base plate and provided with a peripheral slot which forms a flexural joint between the two plates. The thin cavity between the face plate and the

base plate is filled with mercury. The pressure on the face plate is averaged and transmitted by the liquid to an internal diaphram. This internal diaphram is formed by boring the base plate from the rear to provide a diaphram section which will respond to loading by increased radial and tangential strains. Electrical strain gages affixed to the rear of this diaphram undergo resistance change proportional to the applied pressure as a result of the strains induced in the diaphram. The cell measures the total force normal to the face plate from both the solid and liquid phases of the surrounding medium. An overall accuracy of ± 0.5 percent of full load pressure is obtained in the cell.

A pressure cell has been developed in England by P. W. Rowe (36). This cell, which is 1.5 inches in diameter and 1.35 inches thick, is capable of measuring pressures in the range of 0.01 to 0.05 pounds per square inch. The deflections of the diaphram of the cell are measured through the use of a differential transformer. Rowe claims the cell to be free of error due to soil arching and zero wander.

Cooper, VandenBerg, McColly and Erickson (9) have published the results of experiments in which a cell of the diaphram type was used to measure loads transmitted through soils by farm equipment. This cell was two inches in diameter and five-eighths of an inch thick. The diaphram deflections were measured by SR-4 strain gages cemented to the diaphram. The authors reported that a cell suspended in earth gave pressure indications which were comparable to those given by a cell flush in a false bottom, at the same location within the soil mass.

The literature survey on pressure cells provided knowledge concerning the design and functioning of cells which might have been used in this investigation. However, the purpose of this investigation was to obtain pressure measurements in model studies. The success of the model study depended upon the possibility of taking a number of measurements for each loading condition. In order to do this it was necessary to have a small versatile cell. As the funds for the project were limited, it was also necessary to use a cell which could be produced at a relatively low cost. The Goldbeck, Carlson, or Waterways Experiment Station cells would have given results which would have been comparable with other investigations. However, these cells were large and costly; they would not have fitted the requirements of this investigation. The cell developed by Rowe was of a shape which differed greatly from the criteria of the Corps of Engineers and measured only in a very narrow range of pressures. The cell which was developed for this investigation was patterned after the cell used by Cooper, VandenBerg, McColly and Erickson. However, the dimensions and construction of the cell have been modified.

Pressure Distribution

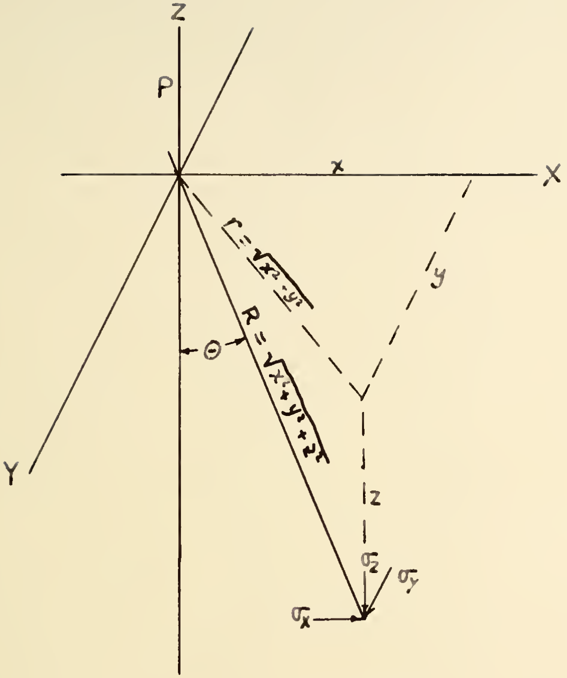
Present methods of determining pressure distributions in pavement systems or in earth masses are, for the most part, based on the classical solution of Boussinesq (4), published in 1885. This solution has been widely used for the determination of stresses under foundations. The Boussinesq solution was developed for a point load, on a semi-infinite, ideally elastic, isotropic and homogeneous solid.

Most soils, and all flexible pavement systems, depart greatly from the assumed idealized conditions. Figure 1 illustrates the Boussinesq solution and presents the equations for obtaining the stresses produced by a concentrated load p, at a depth z, and a horizontal distance r from the line of action of the vertical load. In these equations all stresses are independent of Young's Modulus E of the materials. The vertical stress σ_z is independent of the value of Poisson's ratio.

The point load solution of Boussinesq is not applicable to many foundation problems; therefore, several investigators have integrated his equations over an area and devised methods of computing the stresses under the area. Newmark (31) has developed a method for obtaining the stresses under a corner of a uniformly loaded rectangular area. Love (30) has solved the problem of determining the stresses under a uniformly distributed load on a circular area. He found the vertical normal stress, at a depth z below the center of a circular area with a radius r, which carries a unit load p, to be:

$$\sigma_z = p\left[1 - \frac{z^3}{(a^2 + z^2)^{3/2}}\right]$$

This equation is widely used in pavement design. Palmer (32) has investigated Love's solution, using "approximate methods," and has been able to check his work rather closely. In his conclusions he observes that Love's work indicates that the greatest shearing stresses may be confined within the flexible pavement and not reach the subgrade, if the thickness of the flexible pavement is no less than the radius of a circle having an area equal to the plane of contact between the tire and the pavement.



$$\sigma_z = \frac{3P}{2\pi}\frac{Z^3}{R^5}$$

$$\sigma_x = \frac{P}{2\pi}\left[\frac{3X^2Z}{R^5} - (1-2\mu)\left(\frac{X^2-Y^2}{Rr^2(R+Z)} + \frac{Y^2Z^2}{R^3r^2}\right)\right]$$

$$\sigma_y = \frac{P}{2\pi}\left[\frac{3Y^2Z}{R^5} - (1-2\mu)\left(\frac{Y^2-X^2}{Rr^2(R+Z)} + \frac{X^2Z^2}{R^3r^2}\right)\right]$$

FIGURE I
BOUSSINESQ'S SOLUTION
POINT LOAD PROBLEM

Froehlich (18) has attempted to express the effect of a varying E with depth beneath a concentrated load applied to the surface of a semi-infinite solid. He proposed the following equation, where n is a statically indeterminate parameter, called the Concentration Factor:

$$\sigma_z = -\frac{nP}{2\pi} z^n(r^2 + z^2) - (n + 2)/2$$

This equation is identical with the Boussinesq equation when the factor n is equal to three. Attempts have been made to integrate this equation over a loaded area but without success.

D. M. Burmister (5) (6), of Columbia University, has developed a theory of stresses and displacements, in a layered soil system, in accordance with the methods of the theory of elasticity. The necessary assumptions of the theory of elasticity were made. It was assumed also that essential continuity conditions of stress and displacement across the interface between the layers were satisfied. The continuity conditions were: a) continuous contact and composite action of the two layers, b) continuous uniform support of the pavement layer, c) normal and shearing stresses, and vertical and horizontal displacements must be equal in the two layers at the interface. This theory reveals the relations existing between the physical factors which control the magnitude and distribution of stresses and displacements in a layered system. The theory for the two-layer system has been applied to the design of pavements for airfield runways in the Navy design method (5). The theory of this system has been developed by the use of the equations of the theory of elasticity for the three-dimensional problem in cylindrical coordinates developed by Love (30). The basic equation of settlement, at the center of a flexible circular bearing area, for

the two-layer system, reduces to the Boussinesq equation for Poisson's ratio of one-half, with a multiplying or correction coefficient, F_w. This coefficient is a function of the ratio of the radius of the bearing area to the thickness of the surface layer, and the ratio of the moduli of the two layers. Figure 2 illustrates the two-layer system theory and the difference in normal stress distribution as computed by this theory and the Boussinesq equations for a hypothetical example. The loads are imposed beneath the center of a load uniformly distributed over a circular area.

The problem of stresses in flexible pavement systems is a special case of the overall problem of stress distribution. In pavement systems the materials are definitely layered, with materials of widely varying strengths. In order to establish a rational method of design it is necessary to know the pressure distributions within each of the several layers. Researches which have been performed in the past, have been, for the most part, concerned with a single phase of the distribution and not the overall pattern.

Teller and Buchanan (41), of the Bureau of Public Roads, have investigated the distribution of contact pressures of tires. Measurements were taken by means of the friction on a tape between the tire and the pavement. The results of this investigation indicated that the maximum load intensities occur in two transversely symmetrical zones rather than at the geometric center of the area.

Price (35) of the Civil Aeronautics Administration reports a tire pressure distribution, obtained on a flexible spring-loaded subgrade, as shown in Figure 3.

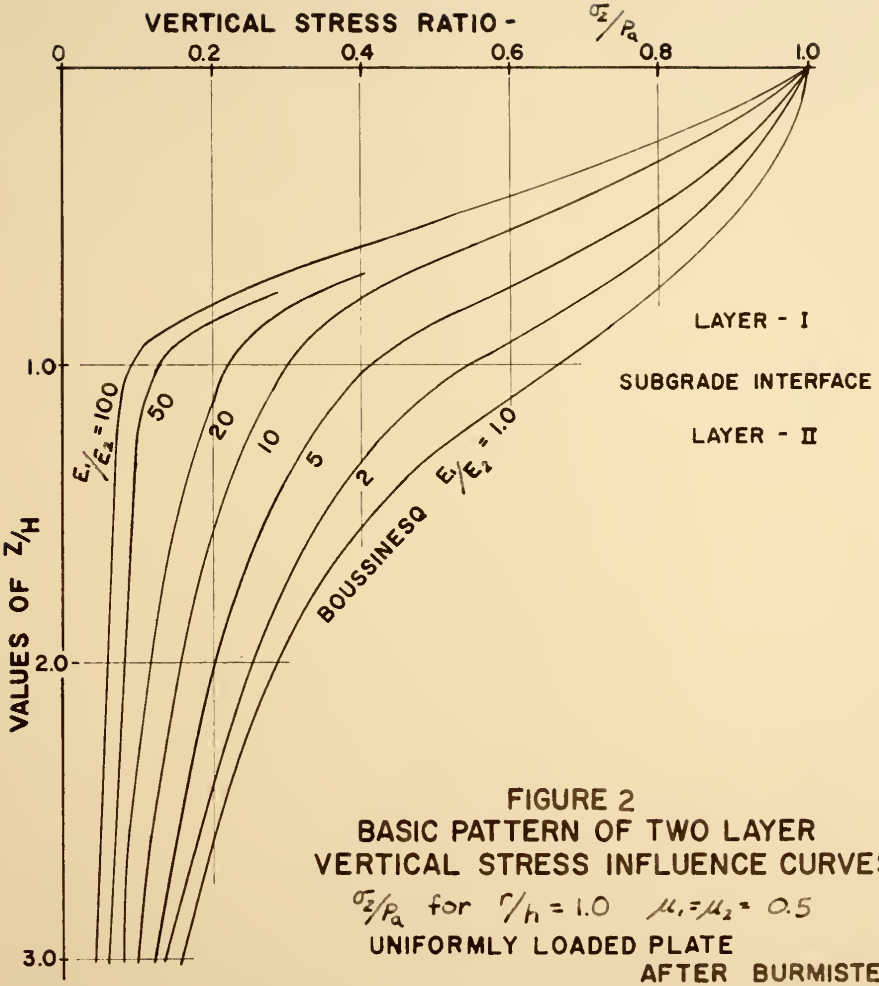


FIGURE 2
BASIC PATTERN OF TWO LAYER VERTICAL STRESS INFLUENCE CURVES
σ_z/P_a for $r/h = 1.0$ $\mu_1 = \mu_2 = 0.5$
UNIFORMLY LOADED PLATE
AFTER BURMISTER

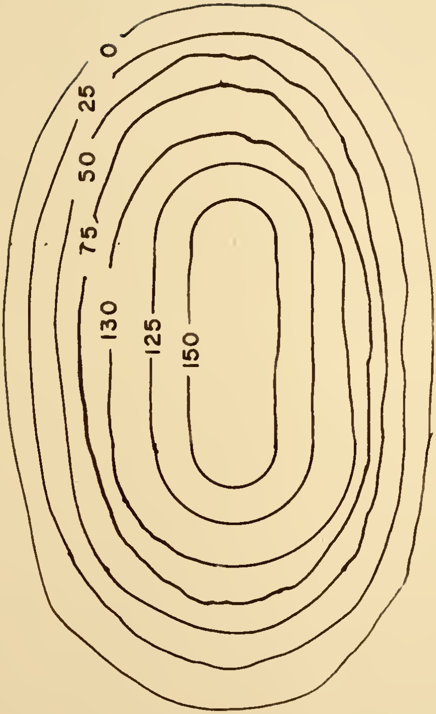


FIGURE 3
PRESSURE DISTRIBUTION
OF A 34×99 TIRE ON A MECHANICAL
SUBGRADE K=310
140 POUNDS AIR PRESSURE
14,000 POUND LOAD

AFTER PRICE

Spangler and Ustrud (40), of Iowa State College, have investigated the vertical pressures transmitted through a flexible type pavement to the subgrade. Their measurements were made with small carbon disk piles, arranged at frequent intervals along elements parallel to the major and minor axes of the tire contact area. The piles were placed in the horizontal plane between the pavement and the subgrade, after being calibrated by means of air pressure. This study also included an investigation of the relation between the tire contact area and the load on the tire, and the tire inflation pressure. The authors concluded that their investigations indicated that the subgrade pressure is distributed in accordance with the typical Boussinesq shaped curve; that the maximum pressure occurs on a small area of the subgrade directly beneath the load; that the magnitude of this pressure is independent of the tire inflation pressure but is dependent upon the applied load; the pressure is inversely proportional to the thickness of the pavement; and that the load-inflation pressure quotient is not a valid criterion for determining the contact area. In a later paper (39), Spangler stated that for a given thickness of pavement and a given load, the pattern of pressure distribution on the subgrade and the maximum pressure directly under the load were unchanged when the inflation pressure of the tire varied from thirty pounds per square inch to seventy pounds per square inch. Under thin pavements the pressures on the subgrade were considerably in excess of the inflation pressure.

Herner and Aldous (25) of the Civil Aeronautics Administration describe the test procedures involved in measuring vertical

stresses transmitted through a flexible surface or base course. In the tests, the natural subgrade was replaced by a system of spring supported plates, which provided a yielding support and permitted accurate deflection and pressure measurements. The plates, each two inches square, formed a platform ten foot square, upon which the base and pavement systems were formed. Each plate was supported by a calibrated spring; therefore, it was possible, by measuring the deflection of each spring, to determine not only the deflection but also the transmitted pressure.

Aldous, Price, and Shearer (2) reported results of the Civil Aeronautics Administration's investigation of pressures transmitted to a flexible subgrade. The following conclusions were given:

> 1. The load-transmission apparatus provides a convenient and relatively accurate means of determining the distribution of vertical stresses through large scale pavement test sections.
>
> 2. For single loads, the pressure-distribution pattern on the subgrade is helmet-shaped, with the maximum generally occurring directly under the center of the load.
>
> 3. The maximum subgrade reaction may be used as a basis for comparing results from different pavement sections and different loading conditions.
>
> 4. The magnitude of the maximum subgrade reaction is influenced largely by 1) the total load, 2) the pavement thickness, 3) the contact area, 4) the type of loading medium, and 5) the physical properties of the paving mixture. Families of curves have been developed to show the interrelationship of these variables for tests conducted on normal gravel base course material supported by a weak subgrade.
>
> 5. The type and physical characteristics of the paving material have similar effects on both

> the load-transmission and triaxial test results, thus offering hope of a correlation between the tests.

Price (35) in a paper presented at the Fifth Annual Soil Mechanics and Foundation Engineering Conference at the University of Kansas stated, "When load is applied to a soil or granular material, the logarithm of the resultant stress at any point is directly proportional to the logarithm of the applied load." He was referring to a load placed at the surface.

Important work in the measurement of stresses in earth masses has been done by the Corps of Engineers at the Waterways Experiment Station, Vicksburg, Mississippi. This work is still continuing, but several reports have been published. (10) (12) (13) The basic program was started in 1946, with tests being performed on a homogeneous soil mass. Stresses and deflections induced by static loads of 15,000, 30,000, 45,000, and 60,000 pounds, simulating the effect of single and dual airplane tires, were measured by means of pressure cells and deflection gages buried in the test section. This test section was 26 feet wide, 50 feet long, and 12 feet deep, with side slopes of 1 on 1. The same installation of cells and gages was tested at differing depths by constructing the section to its maximum height initially and cutting off successive one foot layers of fill as the testing progressed. The test section was constructed of a clayey-silt soil (CL). The soil was placed in four inch lifts and compacted with a sheeps-foot roller at a uniform moisture content. The pressure cells and deflection gages were placed in the compacted fill, after it had reached the proper elevation, by digging shallow pits with sloping

sides, carefully placing the cells and gages, and recompacting the covering soil with air tampers to the density of the surrounding fill. Uniform circular loads were applied to the surface of the test section by means of specially designed flexible plates, and a hydraulic jacking system. Pressure measurements were made by the use of Waterways Experiment Station twelve inch diameter pressure cells. Deflection measurements were taken by utilizing pairs of Selsyn motors. The pressure cell layout was designed to give readings that would permit the resolution of the major and minor principal stresses on planes of symmetry, under single and dual loads. Cells were installed in the vertical, two horizontal, and two diagonal directions. Approximately thirty thousand pressure cell and three thousand deflection gage readings were taken during the testing program. Shear stresses were computed from the stresses measured by the diagonal cells.

Foster and Fergus (15) report the following conclusions developed from data taken in the Vicksburg tests:

1. The distribution pattern of the measured stresses follows the same general shape as that computed from the theory of elasticity for a homogeneous isotropic material.
2. Where the stress values were small, the ratio of the measured stresses to the contact pressure was approximately a constant.
3. Where the stress values were greater than about 10 percent of the contact pressure, the ratio of the measured stress to the contact pressure varied with the total load, the contact pressure, and the area of contact.
4. The use of the Froehlich-Griffith concentration factor did not improve the agreement between the measured and the theoretical stresses.

5. In all cases the ratio of the measured vertical deflection to the contact pressure varied directly with the contact pressure.

6. In general the stress-strain curve developed from the test data has a shape similar to that obtained from "quick" triaxial tests performed on undisturbed samples.

The results of the Waterways Experiment Station investigations indicate that, for a nearly homogeneous section, the stresses approximate the Boussinesq distribution but in general are somewhat higher.

The information provided by the literature research emphasizes by the lack of factual information concerning the pressure distributions in layered systems the need for additional investigation. In order to further the knowledge of stress distributions in layered systems, this research included a study of the pressure distributions in a nearly homogeneous section, and the changes in this distribution as various layers of material were substituted for an equal thickness of the homogeneous section.

PURPOSE AND SCOPE

In order to determine to what extent the present theories of pressure distribution were applicable to the rational design of flexible type pavements, a three-fold study was undertaken.

The first phase of the investigation consisted of the design and development of a small, inexpensive device for measuring the pressures transmitted through a soil mass.

The second phase of the investigation was a laboratory study in which the limitations and uses of the cell were studied and model investigations made.

The third phase of the investigation was a field model study in which pressure measurements were taken for comparison with theoretical values. These measurements were of the pressure distributions under rigid plates, on a nearly homogeneous section, and of the changes in this distribution as various layers of base material were substituted for an equal thickness of the homogeneous section.

DEVELOPMENT OF A PRESSURE CELL

In the development of any device it is essential to know the factors which control the functioning of the device and the limitations within which the device will perform with the specified precision. With due cognizance of prior efforts, a device may then be designed which will best perform the purpose for which it is intended. This approach was used in the design and development of the pressure cell used in this investigation.

Limitations of the Pressure Cell

It is only reasonable to expect that the introduction of a foreign object having radically different elastic properties into a soil mass of assumed homogeneity will disturb the distribution of pressure in the vicinity of the object.

Kögler and Scheidig (29) first called attention to the difficulties of measuring soil pressures accurately with a pressure cell. They pointed out that a cell which is more rigid than the soil would indicate pressures greater than those present in the soil and, conversely, a cell more compressible than the soil would give pressure readings which were less than those in the soil. There can be little question as to the correctness of this reasoning and the natural inference is, that if a device is to indicate true soil pressures, it must possess in itself the same elastic properties as those of the surrounding soil. The cell must deform in all directions to the same

extent as the soil. The possibility of providing a cell with these characteristics is very small; therefore, it behooves the researcher to develop a measuring device which will disturb the pressure patterns as little as possible and yet provide a precise means of measuring these pressures. The extent to which the indicated pressure might deviate from the true pressure will probably vary as some function of the thickness or of the cross-sectional area of the cell and with the applied stresses. If it is assumed that the forces imposed upon a pressure cell are essentially the same as those resisting the penetration of a body into the soil, it would be expected that the pressure indicated by cells of different size would vary with the area, and the indicated pressures would be different in cohesive and in granular soils. It seems reasonable that the presence of a rim around the pressure-responsive area would disturb the pressure-area relationship, because it would tend to alter the distribution of pressure on the central area. There is also the possibility that difficulty may be experienced in providing the same intimacy of contact over both the rim and the diaphram.

Benkelman and Lancaster (3) observed that with the rim type pressure cell there was considerable variation in the readings obtained with differing types of material and differing methods of embedment. They also determined that the type of soil entered into the degree to which readings corresponded to the theoretical values. In plastic clays the physical dimensions of the cells did not produce a significant deviation in the pressure indications.

Many of the limitations of the pressure cell have been determined by research at the Waterways Experiment Station (11). In this report it is suggested that cells mounted on a wall or a rigid base should have a diameter-projection ratio of greater than thirty; the diameter-deflection ratio of the cell should be greater than one thousand; and cells embedded within a sand mass should have a diameter-thickness ratio greater than five. It was also indicated that pressure measurements were in most cases larger than the applied stresses.

Design Considerations

It is evident from the literature that, while little is known of the actual stress distributions around a pressure cell, it is best to design within certain size ratios in order to minimize the deviation of the cell readings from the theoretical values. It was the intent in this investigation to design a pressure measuring device which would deviate from these limits as little as possible, yet would be small enough and of low enough cost that it could be used with convenience in making measurements at various positions below plates of moderate size.

The major limitation on the smallness in size of the cell is the necessity of providing means of measuring deflections of the cell diaphram and of transferring these measurements to pressure readings. After a study of this problem, it was decided that the use of SR-4 strain gages would provide the most accurate and convenient means of measuring the deflections of a small size diaphram. In order to obtain maximum sensitivity it was decided to use two SR-4 gages, one at the

center of the diaphram and another near the edge, connected in series. It was determined by trial that two SR-4 type 18a strain gages could be attached to a one inch diameter diaphram; therefore, this size diaphram was chosen for the design.

An important facet of the design was the determination of the diaphram thickness. This thickness must be commensurate with the sensitivity desired, and the diameter-deflection ratio established by the Waterways Experiment Station. The thickness computations were made by the use of Timoshenko's equation for the deflection of a circular plate fixed at the edges (42).

Equation (1) $$w = \frac{q\,a^4}{64\,D}$$

where w = deflection at center of plate

q = applied uniform pressure

a = radius

$D = Et^3/12(1-\mu^2)$

E = Modulus of Elasticity

t = diaphram thickness

μ = Poisson's ratio

The use of this equation, in a trial and error process, made it possible to select a diaphram thickness which would best fit the criteria of the Waterways Experiment Station and still retain the desired sensitivity. A diaphram thickness of 0.02 inches was chosen and used in the first series of cells. Later, cells with a diaphram thickness of 0.018 and 0.015 inches were constructed for the measurement of the smaller pressures at greater depths below the plate. Sample thickness

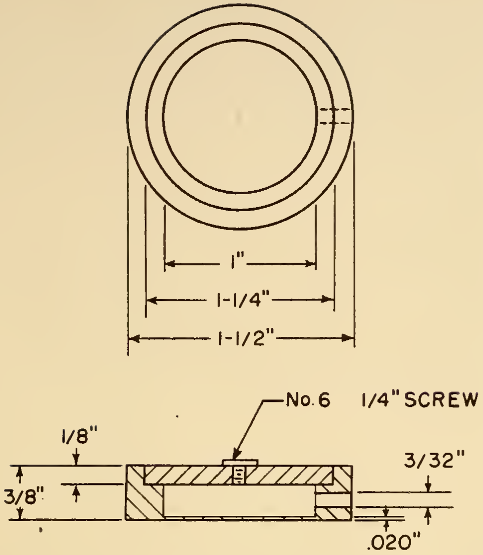
calculations are presented in Appendix A. These computations show that the deflections at the maximum allowable pressure of 64 psi do not satisfy the design criteria; however, it was assumed, and later found to be, that the range of the pressures which would be measured would be of a low enough magnitude to satisfy the criteria.

Stainless steel was chosen as the material of construction of the cell. It is a high yield strength material with excellent elastic properties and will be resistant to corrosion during long periods of contact with moist soil.

The design dimensions of the cell are shown in Figure 4. Because of the difficulty of securing the diaphram to the body of the cell, the cell and diaphram were machined as an integral unit from round stock. Then the diaphram was machined and ground to the design thickness as the last step in construction. The design thickness, determined by the depth necessary for gage installation and wiring, provided a diameter-thickness ratio of four, which was lower than is recommended by the Waterways Experiment Station. This will, however, produce only a slight deviation of the readings in sand and will have no effect in plastic soils (3).

Cell Assembly

The greatest difficulty encountered in assembling the cell was in attaching the SR-4 strain gages to the cell diaphram. The gages of the first cell which was constructed were cemented to the diaphram with Duco household cement. These gages worked very well for a short period of time, but they eventually loosened under the repeated deflection of the diaphram. Armstrong's A-1 Adhesive, an Epon Resin,



MACHINED PRESSURE CELL CASE

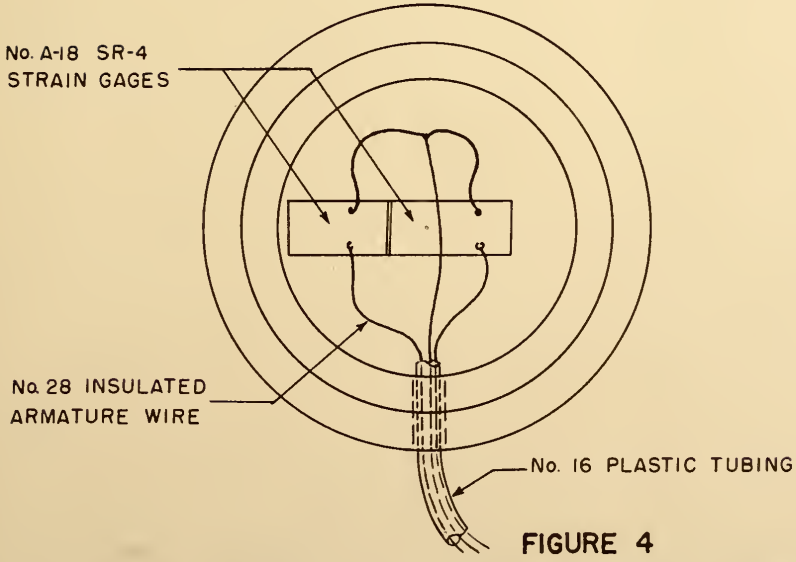


FIGURE 4
GAGE POSITIONS AND CONNECTIONS

was then tried and later adopted as the cementing agent for attaching the gages. To establish a good bond between the gages and the diaphram, it was necessary that the diaphram be thoroughly cleaned and etched with dilute nitric acid.

After the strain gages were placed, it was necessary to connect them to electronic equipment which would measure the change in resistance of the gages as the diaphram deflected. The leads used for this purpose consisted of three lengths of No. 28 enameled armature wire, inserted in a length of No. 16 plastic tubing. The covered leads entered the cell through a small hole in its side, as shown in Figure 4. To prevent the tubing from being pulled from the cell, thereby loosening the gages, copper wire was wound around the tubing on the inside of the cell. The leads were soldered to the connector wires of the gages. It was necessary to thoroughly clean the lead wires before soldering them by burning the enamel from the end of the wire and rubbing the charred section with emery paper.

The cells were to be used in moist, plastic clay soil; therefore, it was necessary that they be waterproof. Several waterproofing materials were tried, including Glyptol varnish, shellac, and asphalt. The best waterproofing was obtained when the gages were completely covered with the Epon Resin and all cell openings were sealed with liquid asphalt.

Instrumentation

Initial calibration readings were obtained with Brush recording equipment, consisting of an analyzer and a pen recorder. The

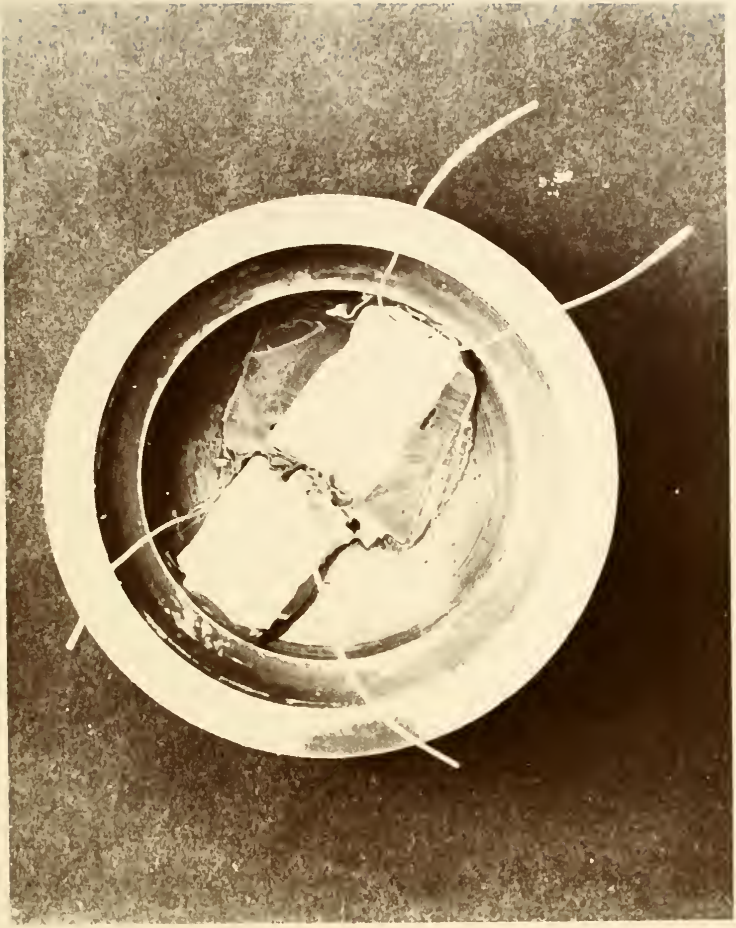


PLATE I

Pressure Cell Interior After Placement of Gages

Brush equipment was chosen in order that a record of dynamic loading might be taken, if it was so desired. This recording system had many desirable features but did not possess the sensitivity and stability required in this research. Accordingly, a Baldwin SR-4 type L strain indicator was substituted for the Brush equipment. The strain indicator afforded an increase in the sensitivity of measurements and in the stability of the circuit. A battery powered strain indicator was used in order that both laboratory and field readings might be made with the same instrument. When measurements were made with more than one cell a switching device was employed.

Cell Calibration

Many measurements were made in order to establish calibration procedures which would be valid under field conditions. The first calibration tests were performed in the triaxial equipment shown in Plate No. II. The pressure cell was placed on the base within the triaxial cell and covered with a flexible membrane, which was then clamped between the lucite cylinder and the base of the triaxial cell. Compressed air entering the triaxial cell forced the flexible membrane against the diaphram of the cell, thereby causing a deflection of this diaphram. The membrane was draped loosely over the cell in order to alleviate the possibility of an error in calibration due to stresses in the membrane. The air pressure in the triaxial cell was measured by means of a large mercury manometer and correlated with the deflections of the diaphram, as measured by the strain gages. This method was later adopted as the procedure to be used for all cell calibration.

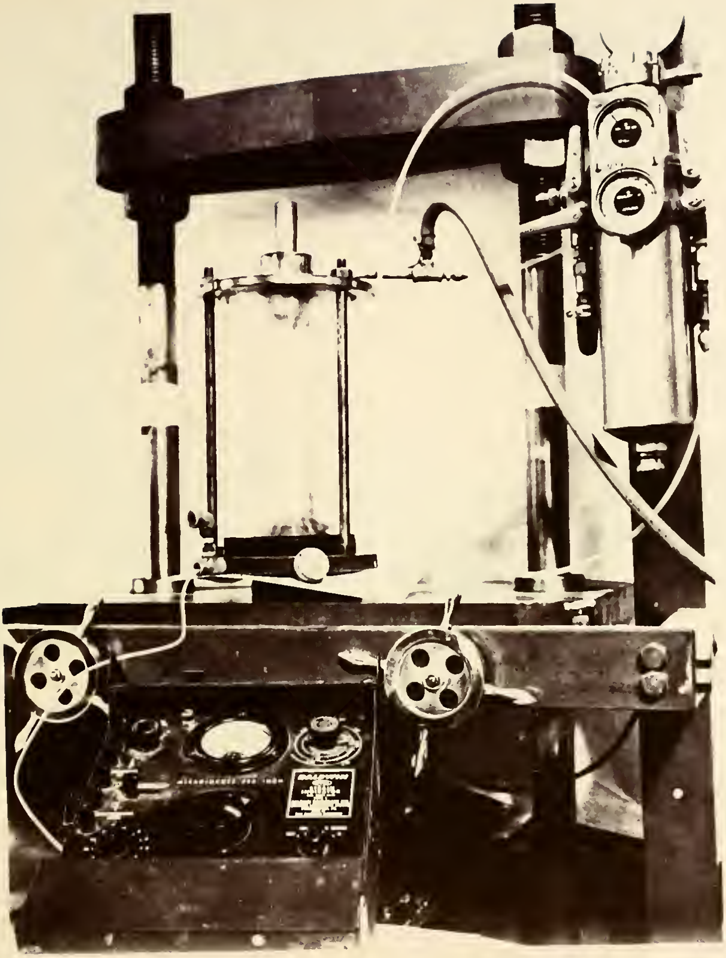


PLATE II

Triaxial Cell Used In Pressure Cell Calibration

PLATE III

Pressure Cell Under Air Pressure

In order to study the effect of the confining medium on the action of the pressure cells, several of the cells that had been calibrated in the air pressure device were re-calibrated in a clay-soil and in a sand medium. The equipment used for this calibration procedure is shown in Figure 5. The cells were buried in clay-soil or sand, whichever medium was being used in the test, in the brass sleeve shown in the sketch. A flexible membrane was placed over the top of the material in the sleeve and again clamped between the lucite cylinder and the base. Air pressure was admitted to the cell, forcing the membrane against the soil. The soil transmitted the pressure to the pressure cell, thereby producing a deflection of the diaphram. The deflections of the diaphram were again correlated with the air pressure to provide a calibration curve.

The calibration data obtained with a clay medium surrounding the cell compared very well with the calibration data obtained with the air. Figures 6 and 7 show this comparison for Cell No. 0. When sand was used as the surrounding medium, the data were very erratic and the correlations were very poor. The membrane was again draped loosely over the brass sleeve to minimize error in the calibration due to stresses in the membrane. The close correlation obtained is attributed to the plasticity of the clay soil and an apparent liquid-like stress distribution within the sleeve. This same type of pressure distribution was evidenced in the work of Benkelman and Lancaster (3).

In order that there would be no doubt as to the validity of the air calibration, for the clay soil medium of the investigation, several of the cells were placed in compacted clay-soil triaxial specimens upon which triaxial compression tests were run. The specimens

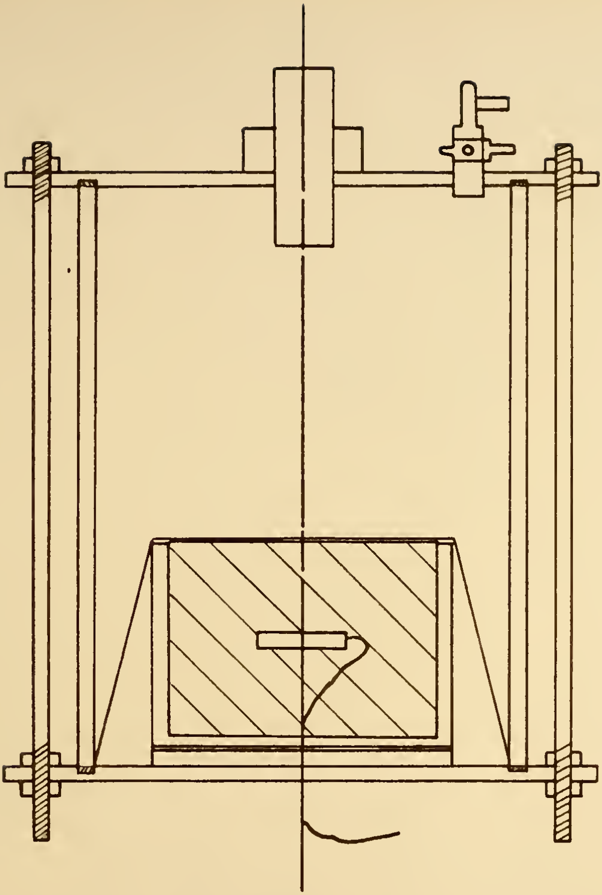


FIGURE 5
APPARATUS FOR CALIBRATING CELL
IN
SAND OR CLAY SOIL

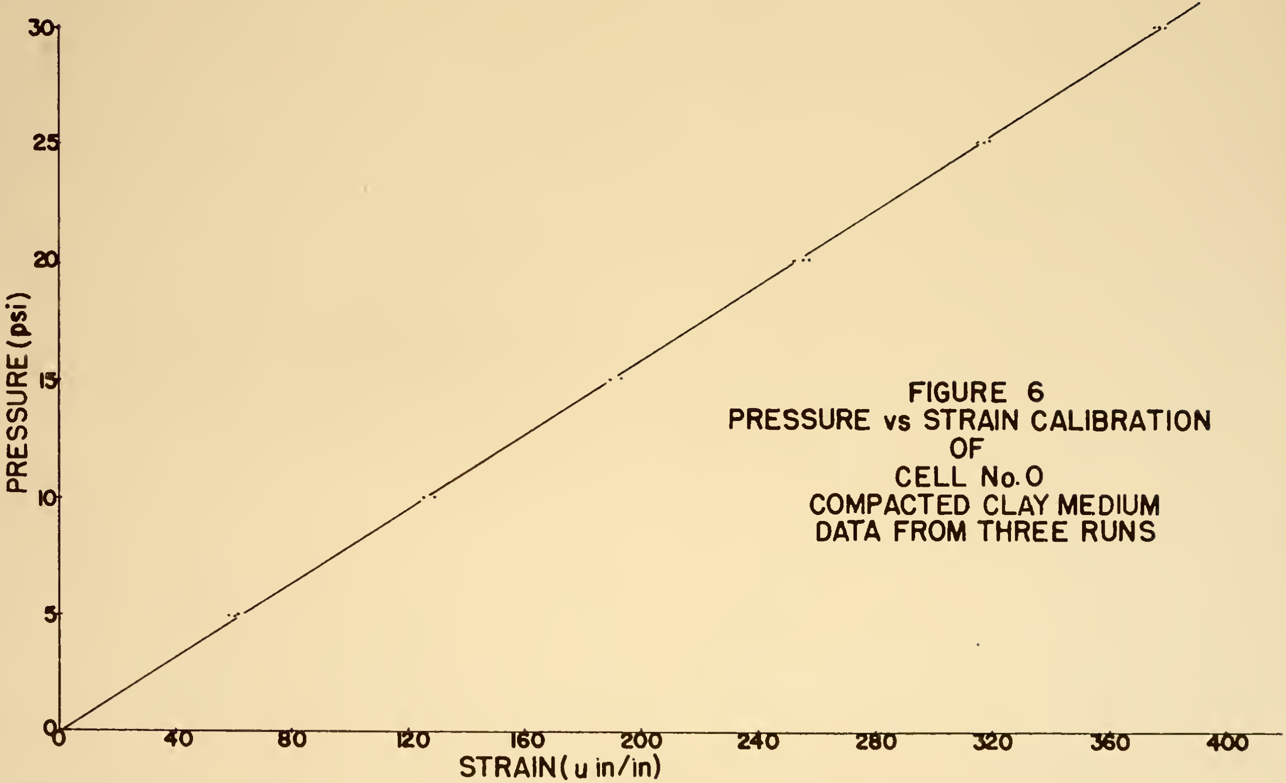


FIGURE 6
PRESSURE vs STRAIN CALIBRATION
OF
CELL No. 0
COMPACTED CLAY MEDIUM
DATA FROM THREE RUNS

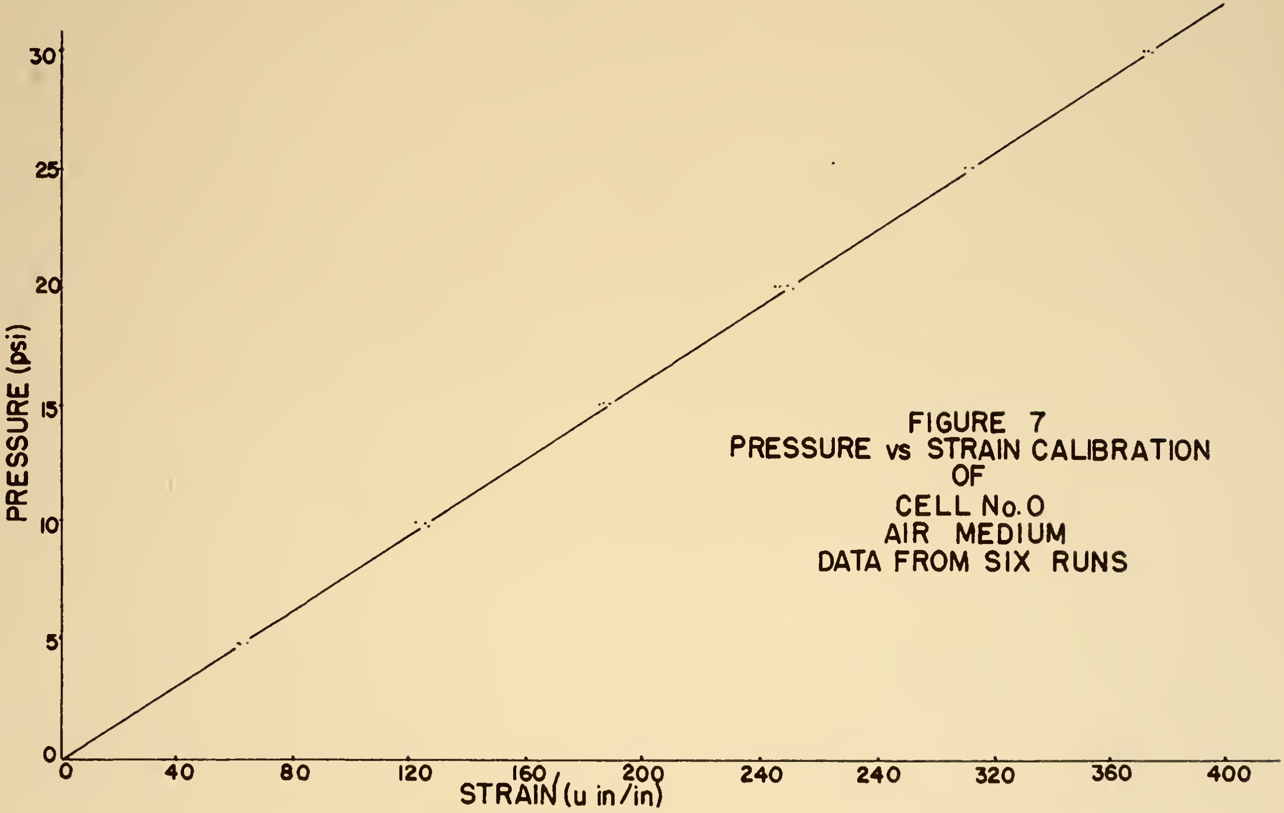


FIGURE 7
PRESSURE vs STRAIN CALIBRATION
OF
CELL No. O
AIR MEDIUM
DATA FROM SIX RUNS

were 6 x 12 inches in size. The cells were placed at the center of the specimen, horizontally and vertically. Readings of the pressures transmitted to the cell, during the test, were taken. In each test the cell was placed in a different plane within the specimen. The triaxial data is shown as Mohr circle diagrams in Figures 8 to 11. In these diagrams a comparison has been made of the pressures measured by the cell and those established by the Mohr circles. The correlations were very good, so good that a further study of them was made. Balla (2a) in his work proposes a stress distribution pattern on a horizontal plane at the center of an elastic specimen, which is higher at the center than at the edges. He also indicates that as the ratio of the vertical stress to the horizontal stress increased, the concentration of stress at the center became higher. The values of the stresses measured in this investigation were slightly higher at the higher ratios. The maximum difference of three percent was not considered to be significant.

The Corps of Engineers, in their large triaxial cell (1), have measured values with the WES cell of 4 to 20 percent higher at the center of a horizontal plane than the expected values. The containing medium in this investigation was a uniform sand. However, the data indicated that part of the over-registration was due to a hysteresis effect, probably due to a densification of the sand.

As a result of this study it was concluded that the measurements made with the cells in the triaxial specimen were a good representation of the actual stresses within the soil. There seems to be little possibility that the cells have over-evaluated the stresses.

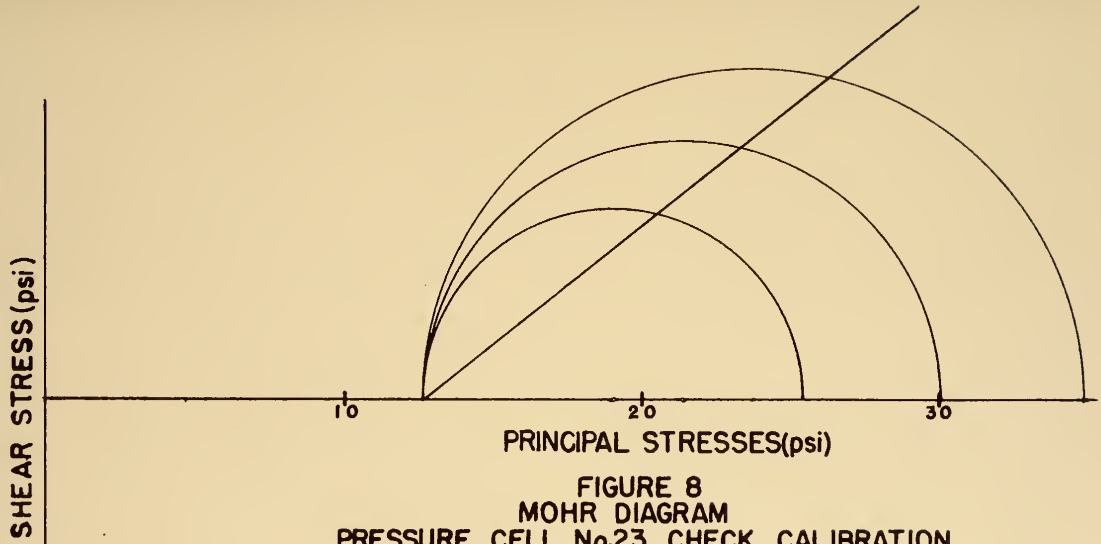


FIGURE 8
MOHR DIAGRAM
PRESSURE CELL No.23 CHECK CALIBRATION
σ_3 = 12.7 CELL ANGLE = 39°

σ_1	CELL READING	MOHR VALUE
25.3	19.94	20.6
30.4	23.50	23.7
35.1	26.62	26.3

CROSBY B SOIL MOISTURE = 17.9%

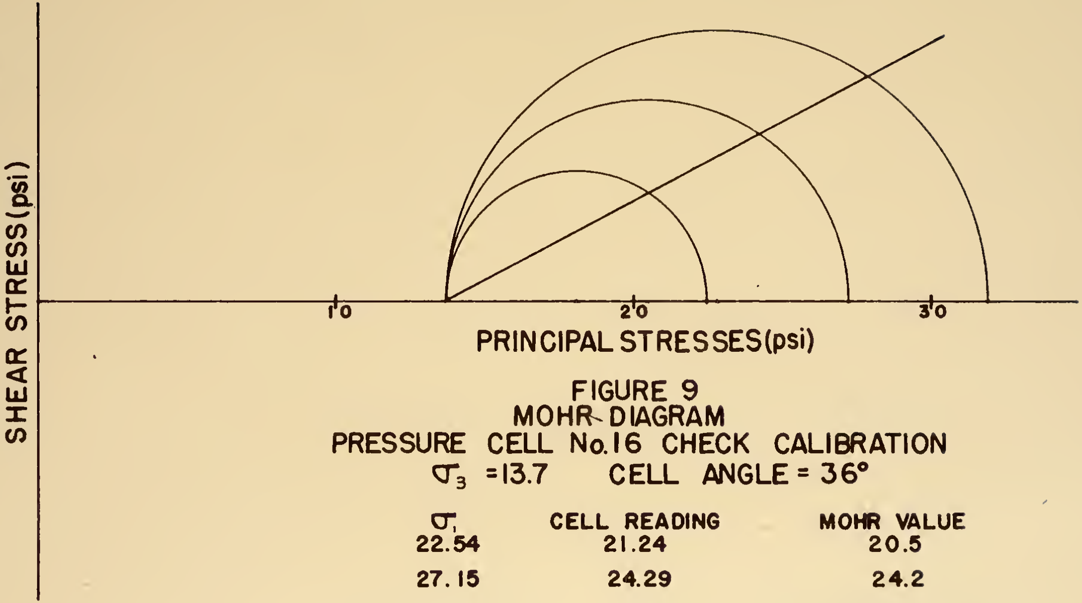


FIGURE 9
MOHR DIAGRAM
PRESSURE CELL No.16 CHECK CALIBRATION
σ_3 =13.7 CELL ANGLE = 36°

σ_1	CELL READING	MOHR VALUE
22.54	21.24	20.5
27.15	24.29	24.2
31.9	28.05	27.8

CROSBY B SOIL MOISTURE = 19.1 %

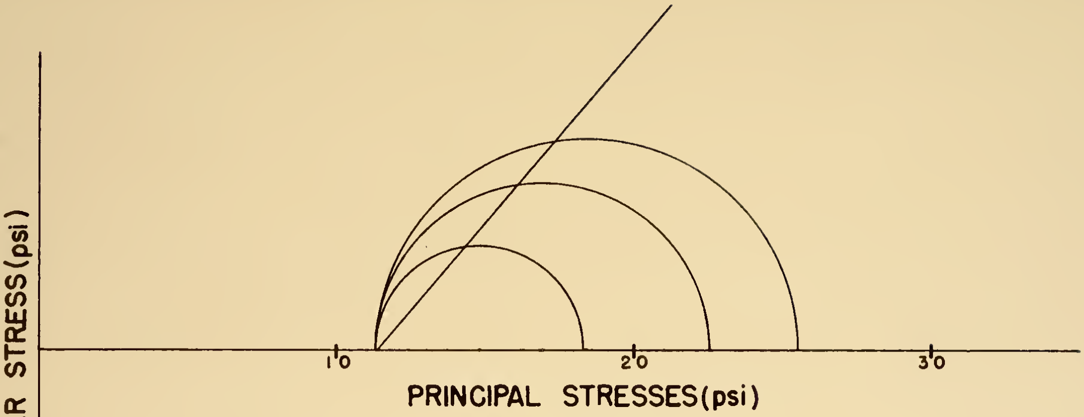


FIGURE 10
MOHR DIAGRAM
PRESSURE CELL No.22 CHECK CALIBRATION
σ_3 = 11.3 CELL ANGLE = 50°

σ_1	CELL READING	MOHR VALUE
18.25	14.58	14.25
22.60	16.74	16.10
25.60	18.00	17.50

CROSBY B SOIL MOISTURE = 18.8%

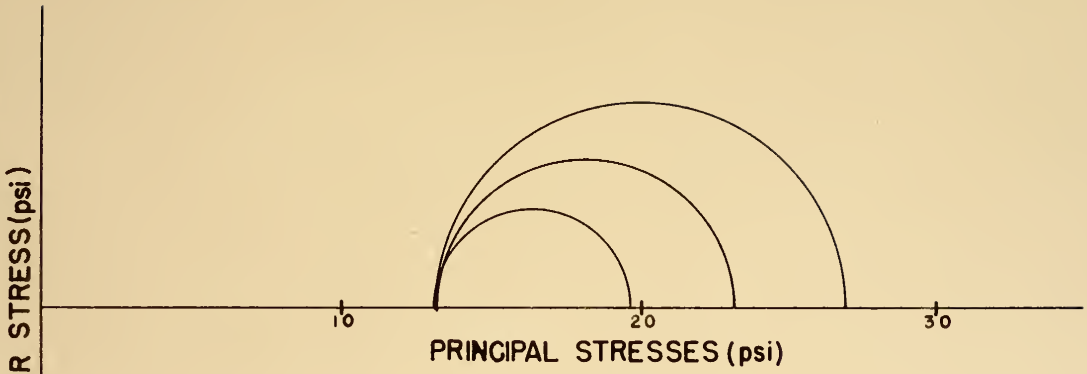


FIGURE 11
MOHR DIAGRAM
PRESSURE CELL No.23 CHECK CALIBRATION
σ_3 = 13.2 CELL ANGLE = 0°

σ_1	CELL READING	MOHR VALUE
19.81	19.21	19.81
23.2	24.05	23.2
27.2	27.92	27.2

CROSBY B SOIL MOISTURE = 20.7%

There is, however, a possibility that the cells have registered values that were slightly lower than the existing values. The triaxial equipment is shown in Plate IV.

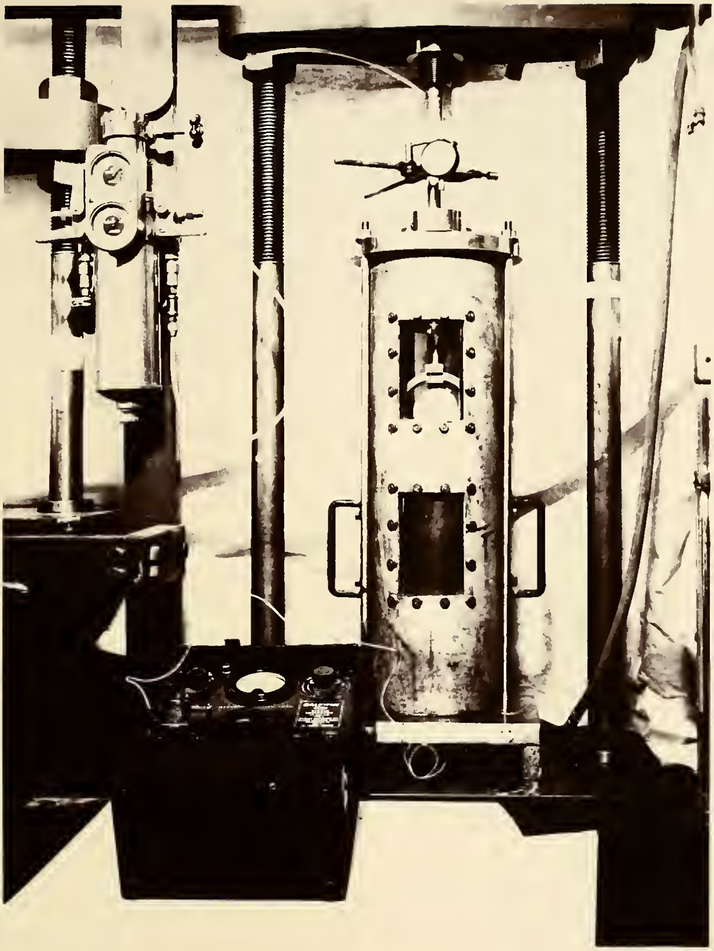


PLATE IV

Triaxial Shear Apparatus

LABORATORY PRESSURE MEASUREMENTS

To ascertain the best procedures for making pressure measurements, and to become familiar with the equipment, it was decided that preliminary tests should be made in the laboratory. These tests were essentially pilot studies and were used only to indicate what might be expected in later studies.

Laboratory Apparatus

The pressure measurements were made in a sandy clay soil placed in a wooden box, the dimensions of which were 18 x 18 x 18 inches. The size of the box was controlled by the test equipment available. In order to minimize side effects, and to reduce the total testing load, a loading plate 5-1/4 inches in diameter was used to apply the load to the surface of the soil. Loads were applied to the plate by a column placed under the loading arm of a soil-test heavy duty loading frame.

Several of the pressure cells were used in each test: therefore, it was necessary to connect the gages to the strain indicator through a switching box.

Laboratory Procedures and Results

In order to observe the limitations of the cells and the electronic equipment, and to determine the best testing procedures, several series of tests, using various test methods, were performed.

The soil used in these tests was a plastic sandy clay. The soil was compacted with a ten pound hammer, having a three inch diameter face, into the box in two inch layers, at a moisture content slightly higher than the optimum moisture content of the soil. The inside and bottom of the box were covered with a plastic sheet in order to minimize moisture change within the soil mass during testing.

The cells were placed in the soil at various depths, and in different patterns, for the several tests. The cell positions are shown in Figure 12 for Series II. Several methods of placing the cells were tried. The best results were obtained when an extension bit was used to drill a hole in the compacted soil into which the cell was inserted. The hole was the same diameter as the cell. It was just deep enough so that the diaphram of the cell was flush with the surface of the layer in which it was placed. A thin covering of soil was carefully compacted over the cells before the next layer of soil was placed and compacted.

The soil was placed to the desired depth in the box, usually fourteen inches, before any load was applied. In the majority of the tests, this provided a twelve inch cover over the gages for the first load application. The first load was applied to this surface through the steel plate and pressure cell readings were taken to determine the load transferred through the soil to the cells. The soil was then removed in consecutive layers of two inches each, with a load being applied and pressure cell measurements being taken after the removal of each two inch increment. This procedure allowed the stresses to be measured for several thicknesses of soil cover with each cell arrangement.

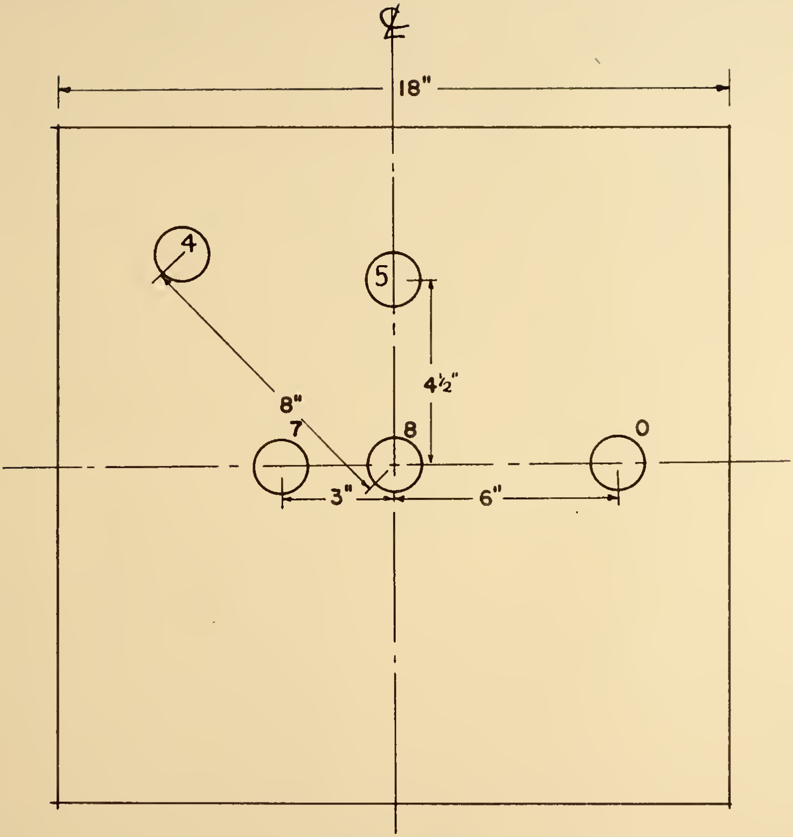


FIGURE 12
CELL LOCATIONS
18" BOX
SERIES II

In all tests the loads were applied to the surface in increments with pressure cell readings being taken after the addition of each increment. In the first series of tests the difference between the initial strain indicator reading at zero load and the reading at full load was considered to be a measure of the deflection of the cell diaphram under full load. Early in the testing it was realized that this method of obtaining pressures was inadequate and led to erratic results. This was caused by the numerous switching operations and the time interval between the initial and final readings.

The second series of tests included not only tests on the soil but also tests in which the upper portion of the soil cover was replaced by crushed limestone or by glacial gravel. This change in materials was made to investigate the change in pressures which might occur if the stresses were transferred through layered materials. In this series of tests the diaphram deflections were determined by the average of the differences between the reading at zero load at the start of the test, the reading at full load, and a zero load reading obtained at the end of the test. The readings obtained in this manner were more uniform and more consistent than the values obtained in the first series. In order to determine the effect of a simulated base course on the pressures, a four inch layer of crushed stone was placed on the surface of the clay at several different stages of the series and was tested in the same manner as the soil. This procedure was repeated with a glacial gravel after the crushed stone was removed. The results of this series are shown in Figures 13, 14, and 15. The cell positions are shown in Figure 12. Values calculated from the Boussinesq

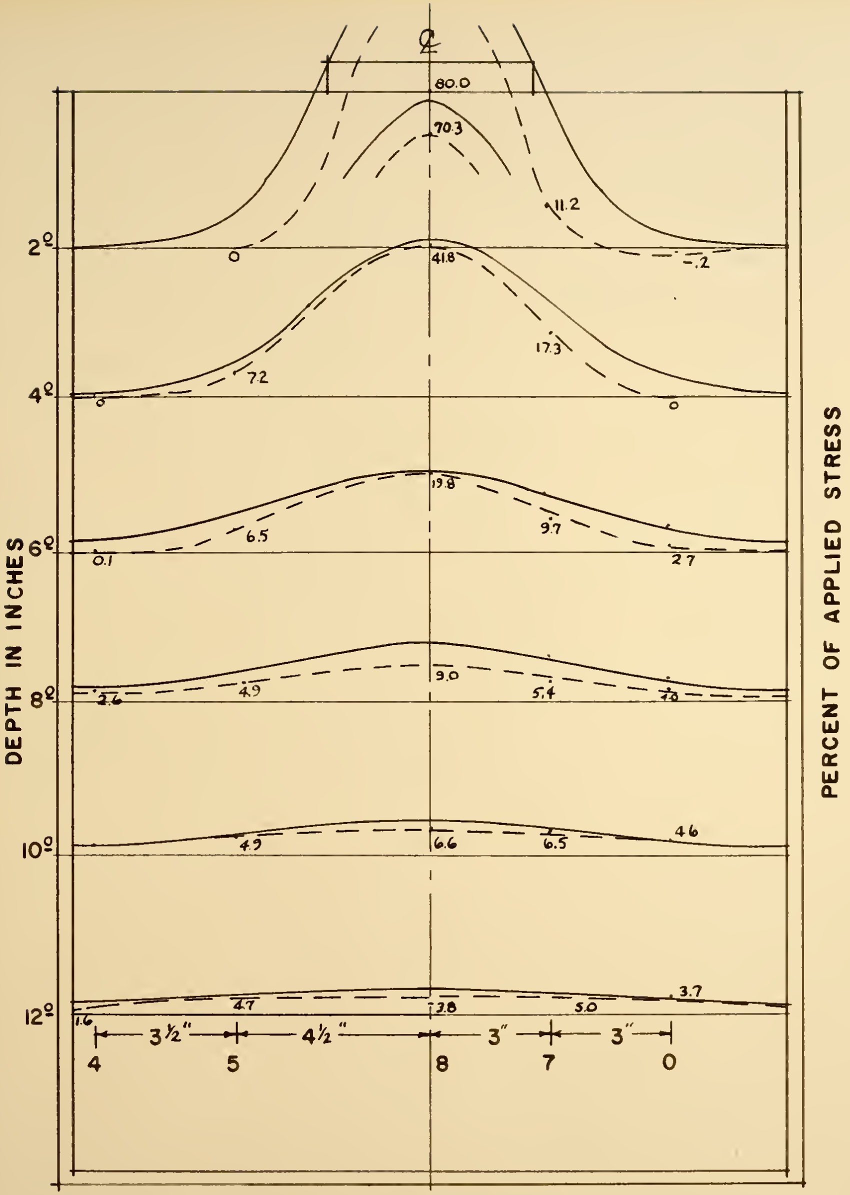


FIGURE 13
LABORATORY PRESSURE CELL DATA
SOIL COVER ONLY
SERIES II

-- MEASURED
— THEORETICAL
(BOUSSINESQ)

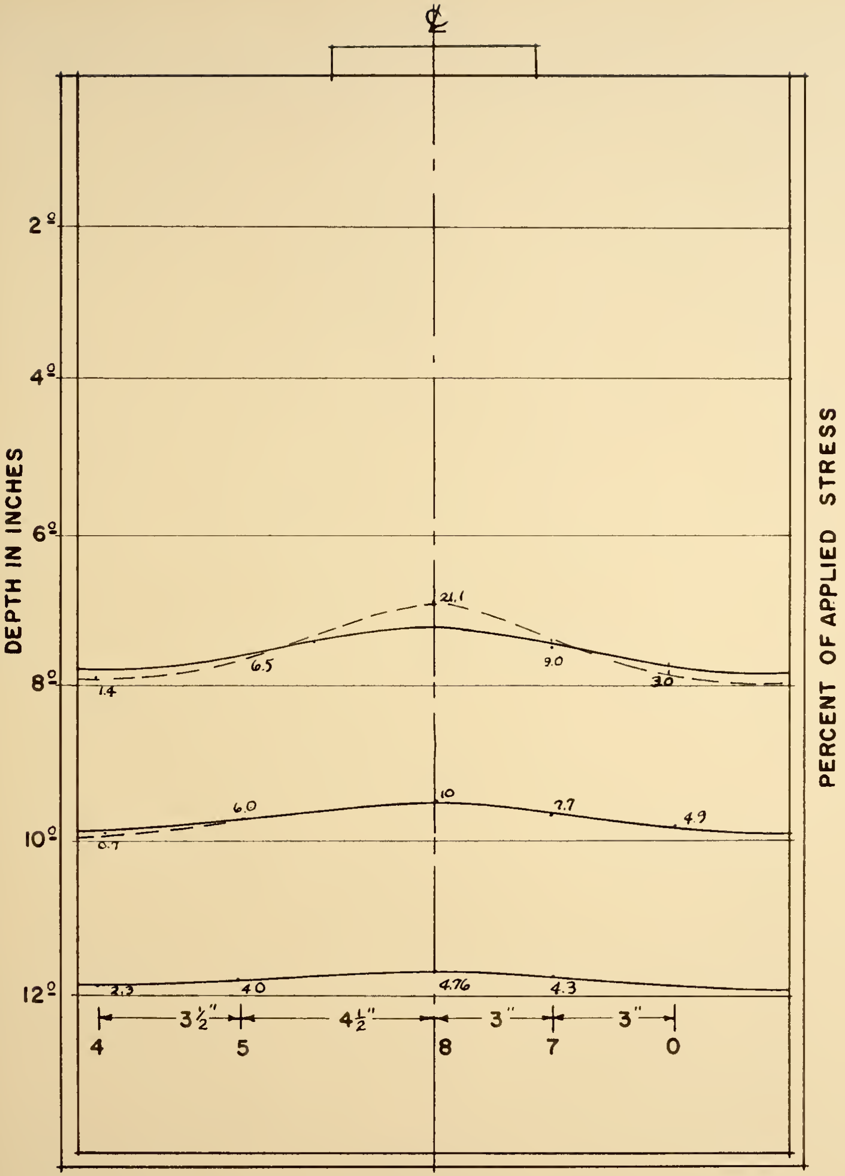


FIGURE 14
LABORATORY PRESSURE CELL DATA
SOIL WITH 4" CRUSHED STONE
SERIES II

-- MEASURED
— THEORETICAL
(BOUSSINESQ)

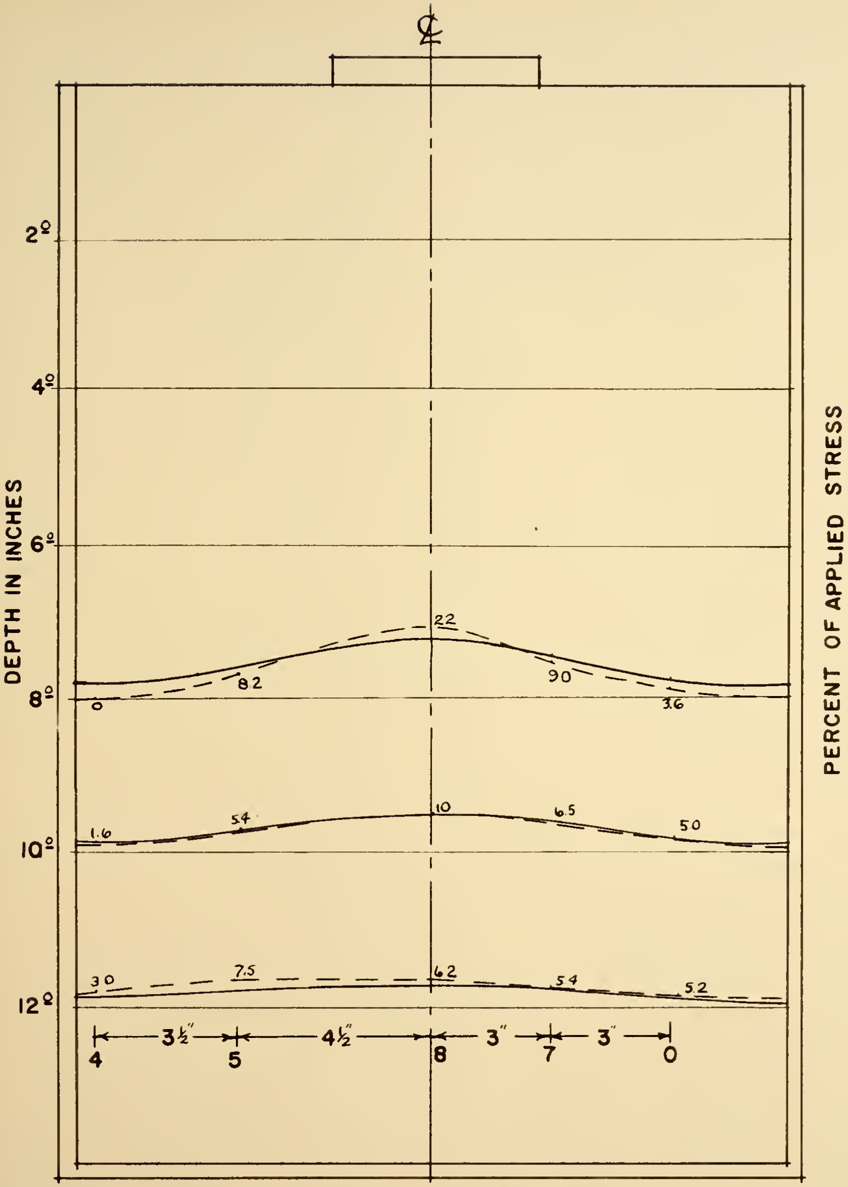


FIGURE 15
LABORATORY PRESSURE CELL DATA
SOIL WITH 4" GLACIAL GRAVEL
SERIES II

-- MEASURED
— THEORETICAL
(BOUSSINESQ)

theory for a uniformly loaded plate are also plotted solely for comparative purposes. It is recognized that this is not a valid comparison, theoretically, but it does aid in determining the validity of the normally used method.

A third series of tests were performed on the clay soil with several changes in procedure. In this series the loading and reading procedures of the second series were followed, but after the final zero reading was taken the full load was again applied as a unit and a reading taken. Then the load was again removed and a final zero reading made. This loading and reading procedure supplied four values of the change from zero load condition to full load condition. The cyclic loading did not affect the pressures transmitted to the cells. Another innovation in this series was the measurement of the vertical displacement of the loading plate with Ames dials. This was done to develop the technique of making these measurements. The results of this series and the cell positions are shown in Figures 16 and 17.

Discussion of Results

The experience gained in performing these laboratory tests was very valuable in the field portion of this research. Satisfactory testing procedures were developed, techniques of placing the cells and wiring the circuits were greatly improved, and methods of data recording and processing were established.

The usefulness of the data taken in these tests was considered to be limited because of the size of the box and the plate. However, a study of the figures depicting the results disclosed good symmetry

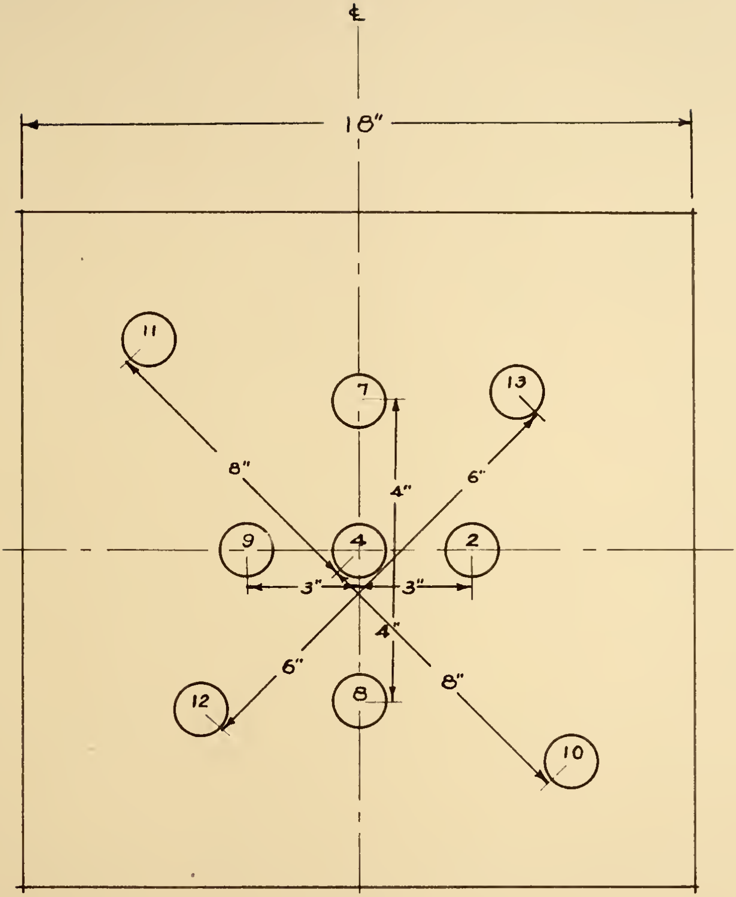


FIGURE 16
CELL LOCATIONS
18" BOX
SERIES III

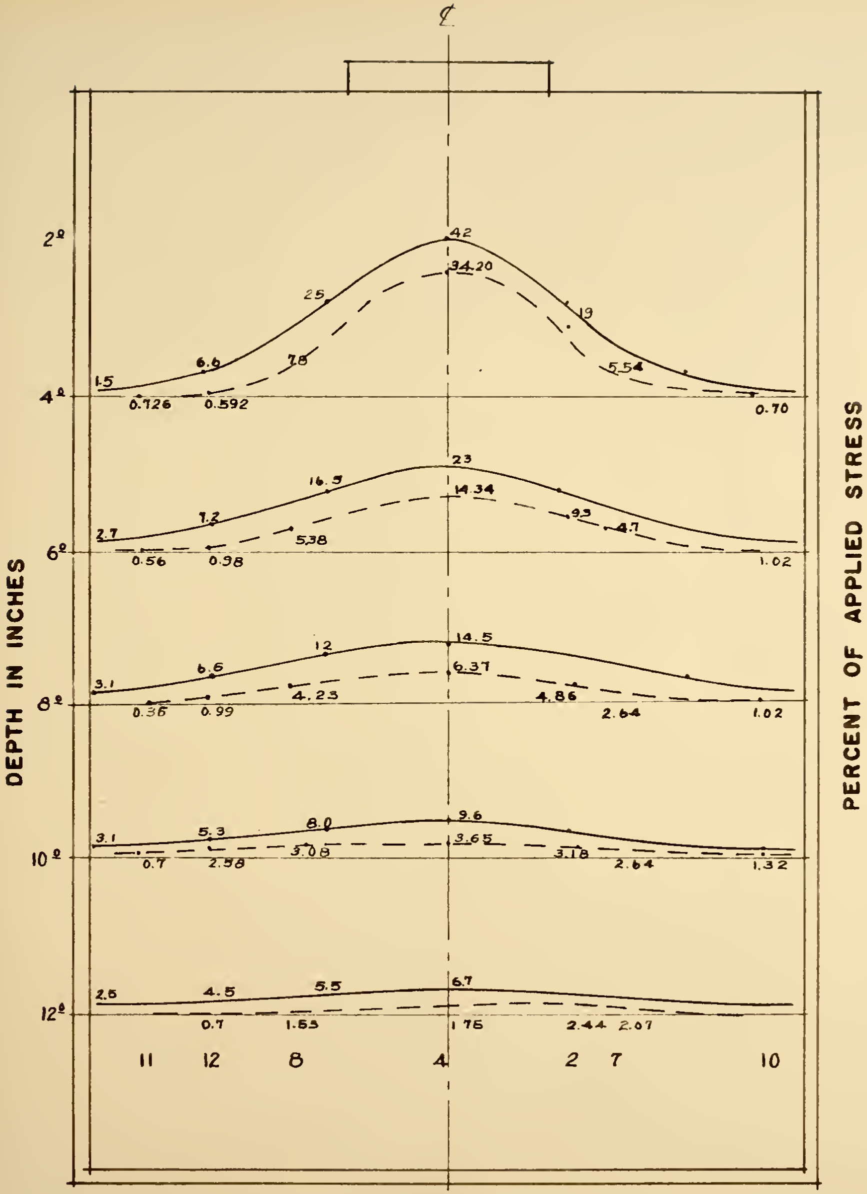


FIGURE 17
LABORATORY PRESSURE CELL DATA
SOIL COVER ONLY
SERIES III

--- MEASURED
— THEORETICAL
(BOUSSINESQ)

in the distributions and fair correlation with the values predicted by the use of the curves established by Foster and Ahlvin (16). The values obtained by the pressure cells tended to be less than the predicted values. This trend is attributed to the arching of the soil in the small box used in the study. When the base course materials were used in the study, the measured pressures were somewhat higher. However, although it was not considered to be significant, this factor was studied further in the field work.

FIELD PRESSURE MEASUREMENTS

The preliminary proposals of this study were based on the premise that all testing would be done in the laboratory. However, the results of the pilot studies indicated serious side effects from the small box. In order to eliminate the side effects for the large size plates it would have been necessary to use a box so large that the available testing equipment would have been inadequate. Therefore, it was decided that the tests with the larger size plates would be performed in the field, in such a manner that side effects would be minimized or completely eliminated.

Pressure Cell Installation

The plan for this section of the investigation called for the measurement of pressures at various depths within the soil mass under several transmitting systems. In order to work above ground, to minimize flooding of the project, and to be able to change the thickness and type of cover readily, the arrangement shown in Plate V was designed and constructed. A pit, three feet deep and eight by eight feet in plan, was excavated in an area of Crosby B soil at the Purdue University School of Civil Engineering test road site. The material removed from the pit was placed on, and under, canvas to minimize the loss of moisture during the construction period. A retaining structure, made with four by four timbers, was erected to a height of one foot above ground level. This structure was arranged so that by removing or adding

PLATE V

Compaction of the Soil in Test Pit

successive side members the contained materials could be reduced or increased by two inch increments of depth. This arrangement provided a variation in depth of cell cover of one foot, in two inch increments, thereby allowing a number of pressure determinations for each cell installation.

The soil which was removed from the excavation was replaced by compacting it in two inch lifts with the gasoline powered vibrator shown in Plate V. The moisture content of the soil was such that the material was within the lower limit of the plastic range. Consistency control was maintained by the use of a Proctor needle. The first group of pressure cells was placed exactly three feet below the top of the timber frame and one foot above the interface between the compacted and the natural subgrade. The relative positions of these cells are shown in Figure 18. The cells were placed in holes drilled with the extension bit and carefully covered with compacted soil before the next layer of soil was placed. Cells were placed in the same manner at two feet and one foot four inches below the top of the framework. This arrangement of cells provided for pressure measurements at three levels for each thickness of cover used. The use of several thicknesses of cover made it possible to obtain a good distribution of measurements throughout the soil mass. Before the fill could be raised above the ground level, a very heavy rain flooded the project. The compacted soil absorbed some moisture and softened to some extent. Two cells in the upper group had to be replaced because of the moisture. After the project was cleaned up and dried out, the fill was placed to the top of the framework. A moisture barrier of plastic was placed between

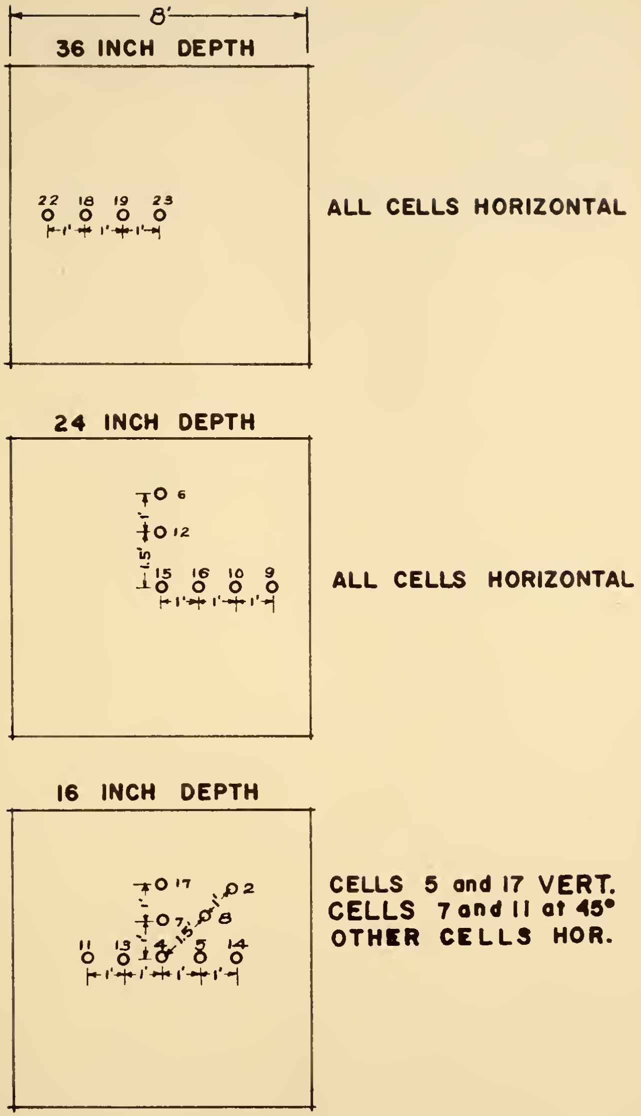


FIGURE 18
PRESSURE CELL LOCATIONS
SERIES I

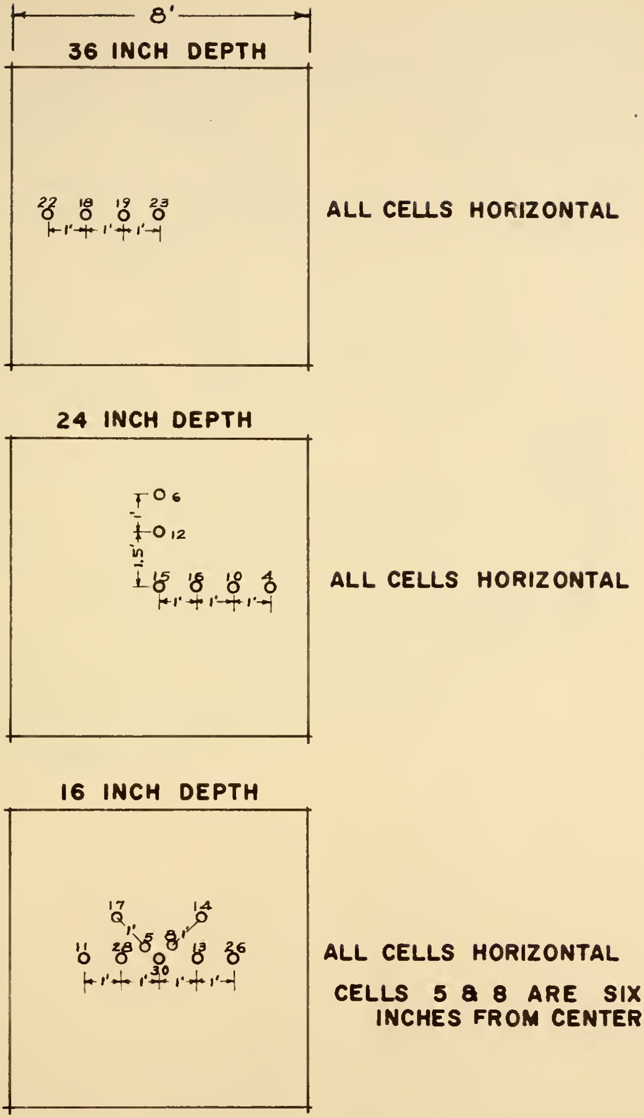


FIGURE 19
PRESSURE CELL LOCATIONS
SERIES II

PLATE VI

Placing the Cells

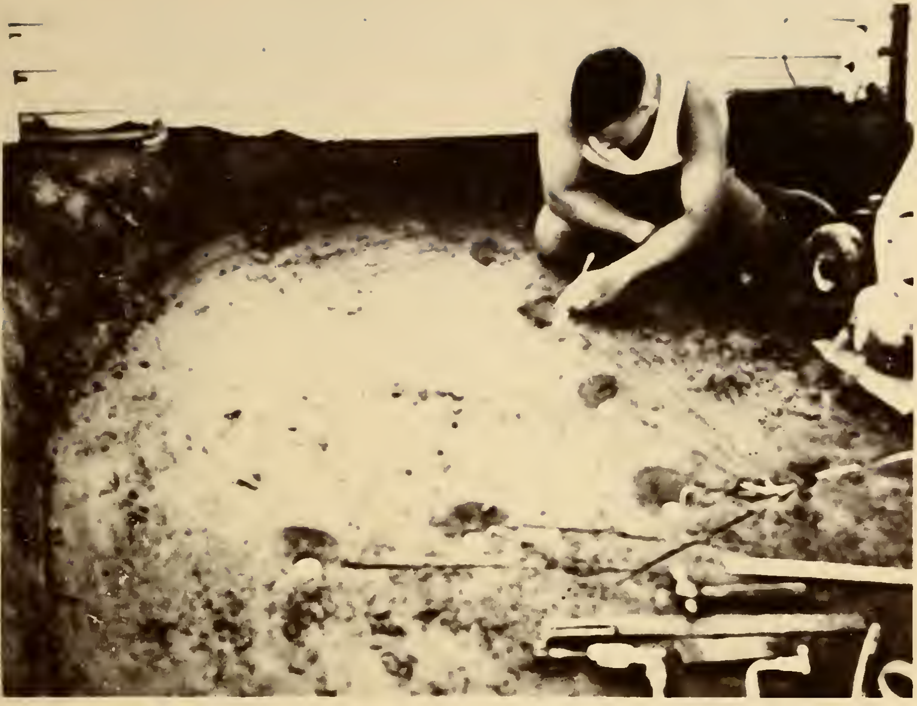


PLATE VII

Cells at Two Foot Depth

Series I

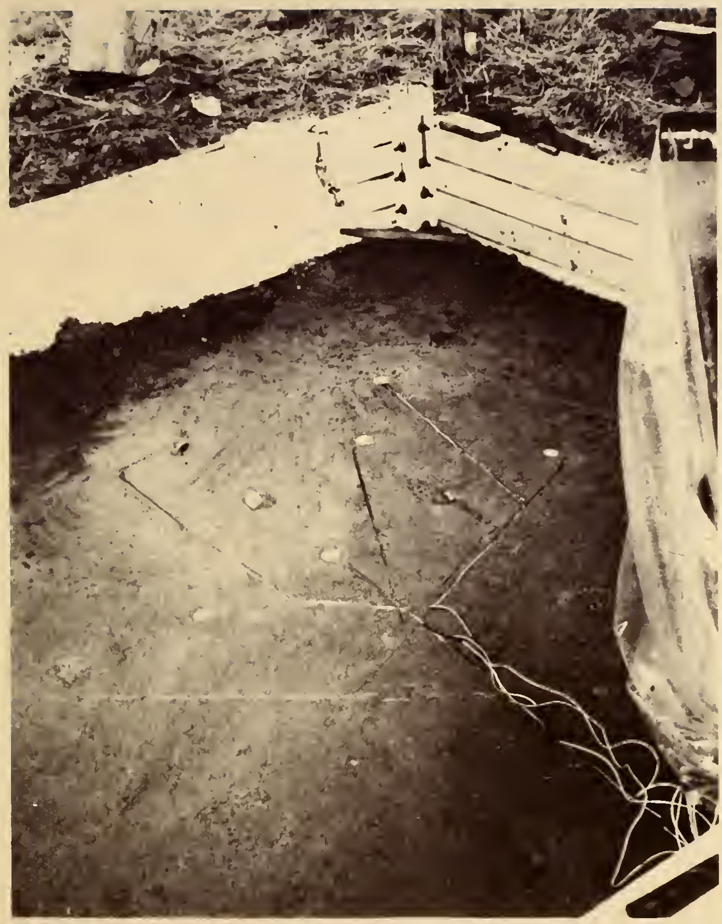


PLATE VIII

Cells at Sixteen Inch Depth

the fill and the wooden frame. Moisture contents, densities, and shear strengths of the compacted soil are included in Appendix C.

Load Test Apparatus

In order to enhance the possibilities of establishing relationships of pressure, area, snd depth, three sizes of plates were used for applying load to the surface of the system. The plates were 7-3/16, 12, and 18 inches in diameter. Loads were applied to the plate by jacking against a soil-test load test frame with a hydraulic jack. The jack was calibrated before the start of the testing and several times during the testing period. Ames dials were used to measure the vertical deformations of the plate due to load. Pressure determinations were again made by measuring the deflections of the cell diaphrams with the strain indicator. The entire test area was enclosed in canvas as soon as construction was completed. The equipment used for compacting the soil and base material is shown in Plate V. The testing equipment is shown in Plates X and XI.

Field Procedures

To obtain as much information as possible, the testing procedures were carefully planned. Tests were run on each of the three plates, on each exposed surface of the clay-soil subgrade, and on each cover layer of compacted base course material.

The first tests were run on the compacted clay-soil surface at the maximum depth of cover, sixteen inches, over the upper group of pressure cells. The largest plate was used first, then the smaller ones in order of size. This provided a smooth, level surface for the contact

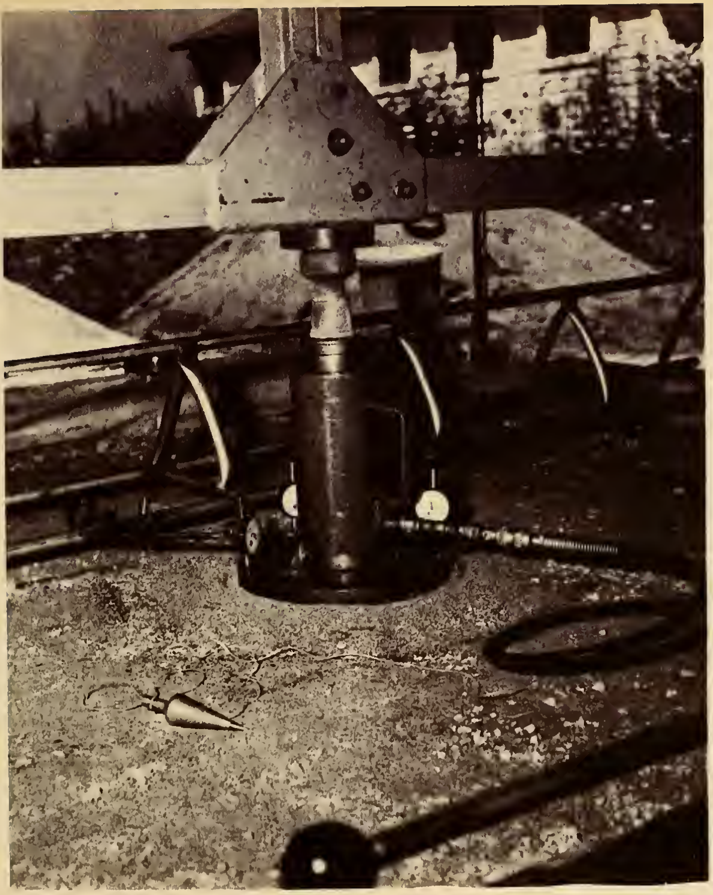


PLATE IX

Load Test Apparatus

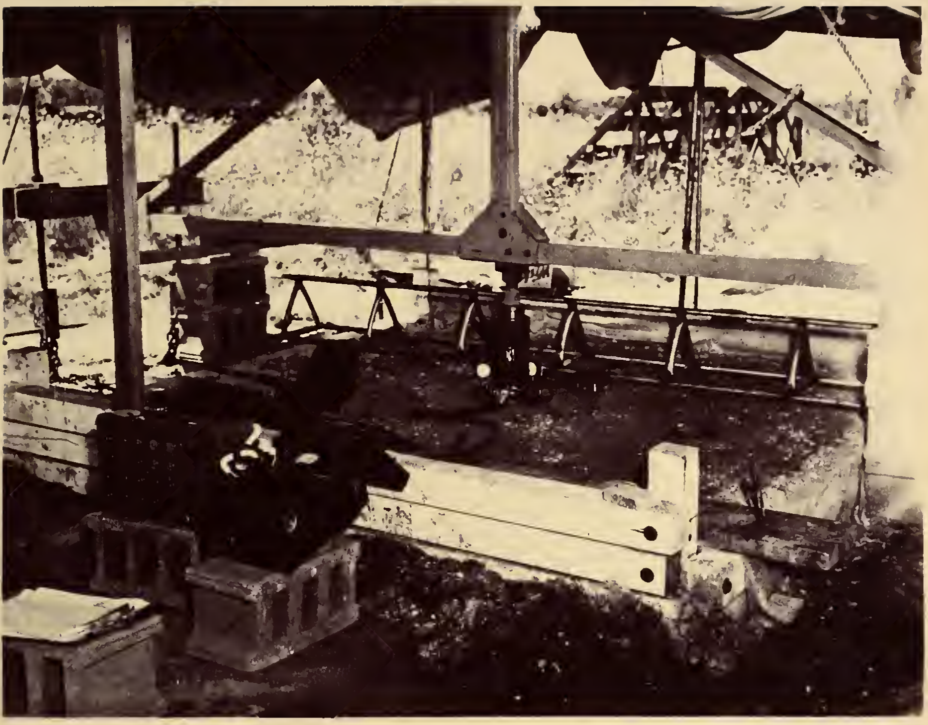


PLATE X

Field Test Equipment

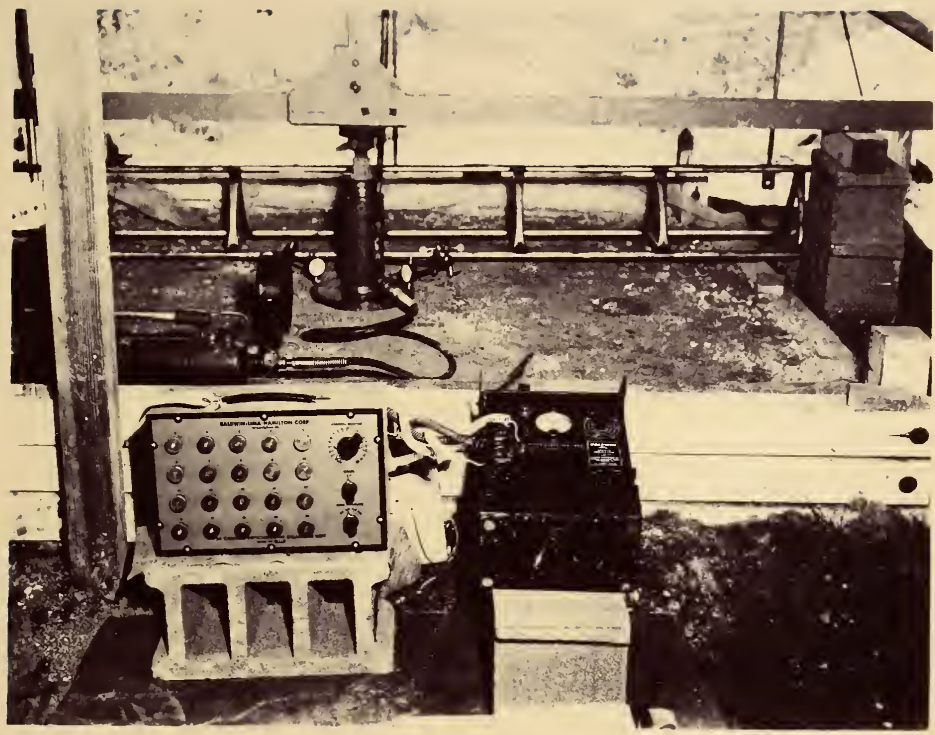


PLATE XI

Switch Box and Strain Indicator

area for each plate. There is no doubt that there was some change in density of the material, because of this method of testing, but the effect was small in most instances. After the tests with the three plates has been run and pressure cell measurements taken, four inches of the soil was removed and the tests repeated. Before the next four inches of soil was removed, a four inch layer of crushed limestone base material was compacted on this surface, by vibration, and the tests run on the surface of the limestone. The base material was then removed, another four inch increment of the soil taken off, and the tests repeated. In both series of tests, eight inch layers of base were also included. In the second series of tests a twelve inch layer of base was placed and tested.

The tests were run as load tests, using the standard load test equipment. The load was applied to the plates with a hydraulic jack, in increments of 500 pounds on the small plate and 1,000 pounds on the two larger plates. After the application of each increment of load a strain indicator reading was taken on each cell. The readings were taken immediately after the load application, over a period of approximately five minutes. The pressure exerted on the cell was determined by averaging the four differences between full load and zero load, as explained in the discussion of laboratory procedures. This method proved to be quite effective, especially with several cells that developed considerable zero drift. In such cases the first of the four values, that over the longer period of time, was discarded and the final three averaged to compute the pressure.

Results

Tables 5 to 22 of Appendix C summarize all of the field pressure measurements taken in this investigation. Each table contains the information pertaining to a series of tests, with the three plates, on a single test surface. The tables are grouped according to the aggregate cover tested, 0, 4, 8, and 12 inches respectively.

Results are presented in curve form in Figures 21 to 30. The curves present the vertical pressure distributions, as determined by the pressure cell measurements, in terms of percent of the stress applied at the surface. Figure 20 presents the stresses as calculated by the Boussinesq method for a uniform load on a circular plate.

The test data for the Crosby soil and the crushed limestone base material is summarized in Tables 23 and 24 of Appendix C. There was some variation in the moisture content and density of the subgrade in Test Series I. This material was placed during a period of excessive rainfall. The fill was flooded and absorbed moisture with a resultant softening of the material. The excessive moisture also resulted in the failure of several of the cells during the test period. The subgrade of Test Series II was much more uniform and of higher strength.

The crushed limestone base, compacted by vibration, seemed to produce a dense surface of fairly high strength. However, the base for Series I proved to be rather weak; therefore, it was decided that in the second series the compacted base should be allowed to stand at least twenty four hours before being tested.

The data obtained from the cells placed at various angles to the horizontal are included in the data tables in the appendix.

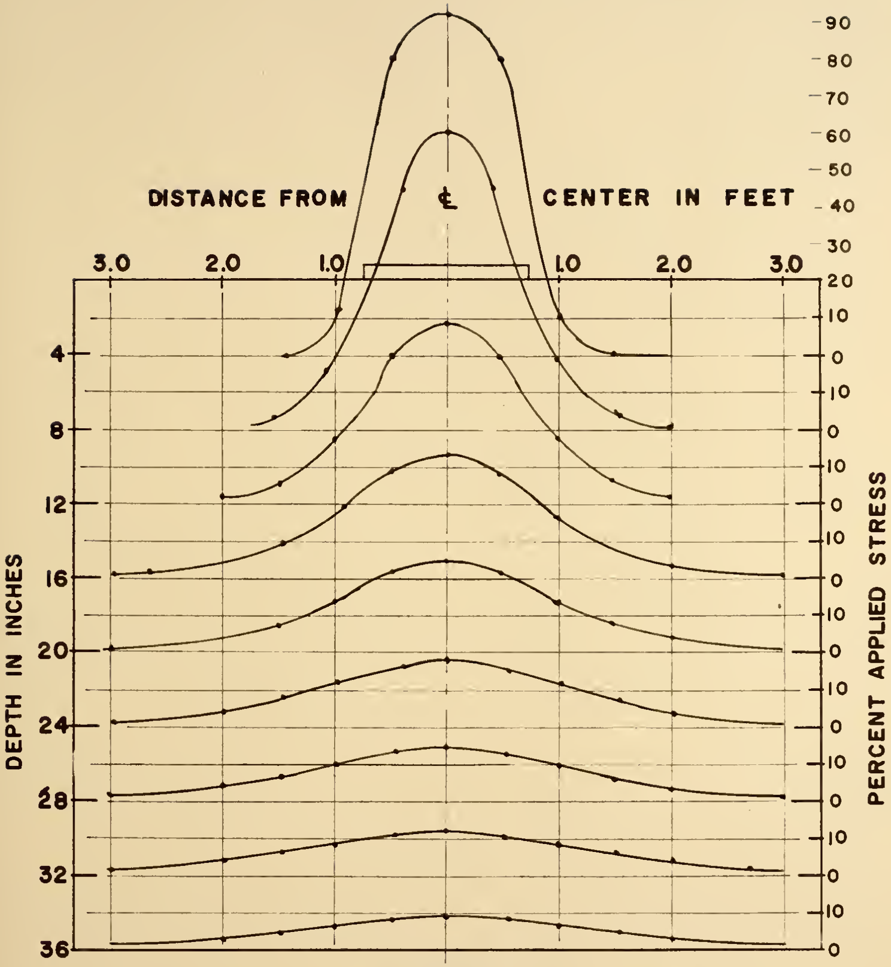


FIGURE 20
CALCULATED VERTICAL STRESSES
AS PERCENT OF APPLIED STRESS
18" DIAMETER PLATE
HOMOGENEOUS MATERIAL
PRESSURE SCALE: 1" = 40 %
UNIFORMLY LOADED PLATE—(BOUSSINESQ)

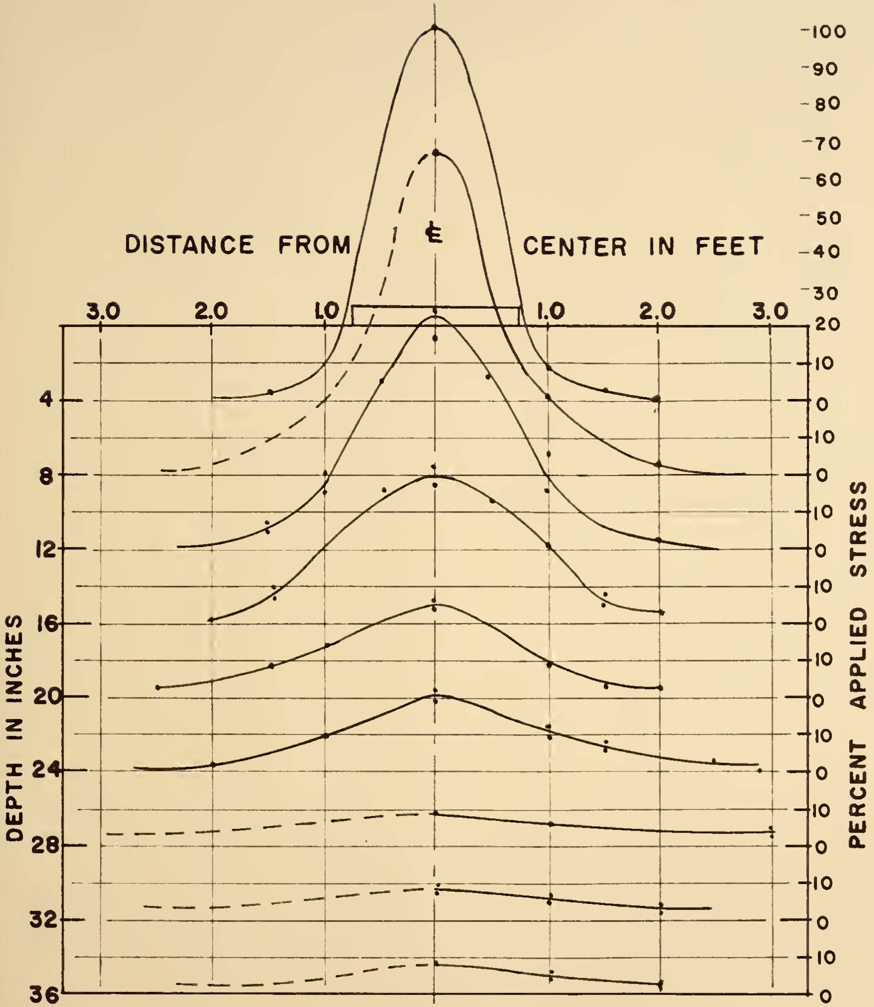


FIGURE 21
MEASURED PRESSURES
AS PERCENT OF APPLIED STRESS
18" DIAMETER PLATE
SUBGRADE ONLY
PRESSURE SCALE 1"= 40 %

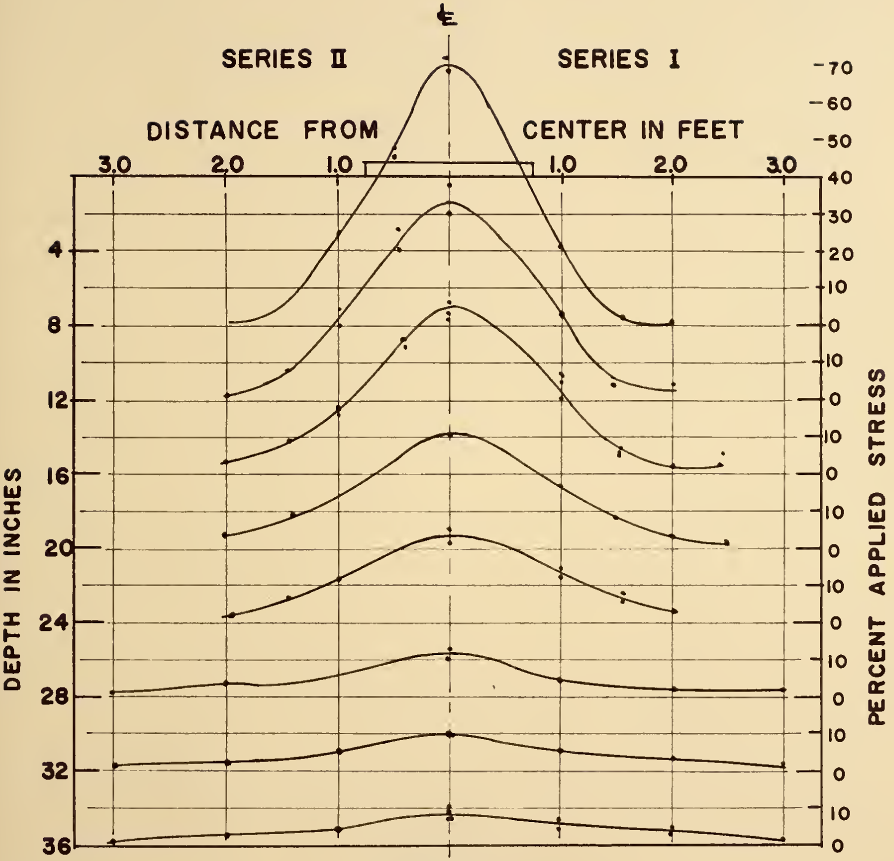


FIGURE 22
MEASURED PRESSURES
AS PERCENT OF APPLIED STRESS
18" DIAMETER PLATE
4" BASE MATERIAL
PRESSURE SCALE 1" = 40 %

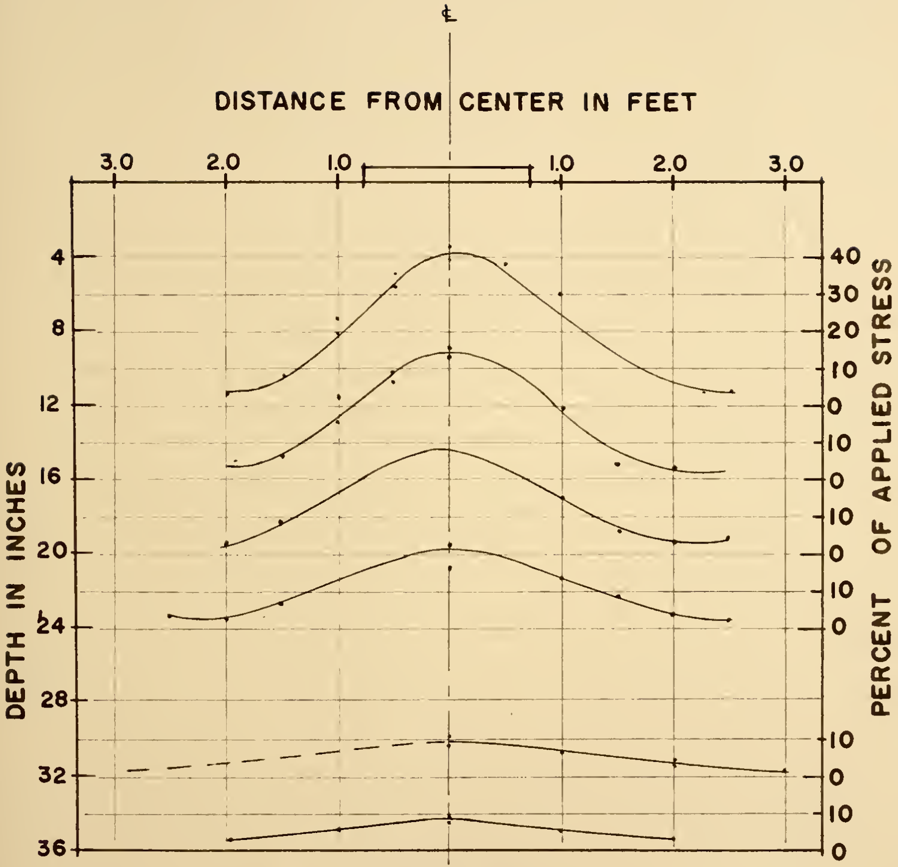


FIGURE 23
MEASURED PRESSURES
AS PERCENT OF APPLIED STRESS
18" DIAMETER PLATE
8" BASE MATERIAL
PRESSURE SCALE 1" = 40%

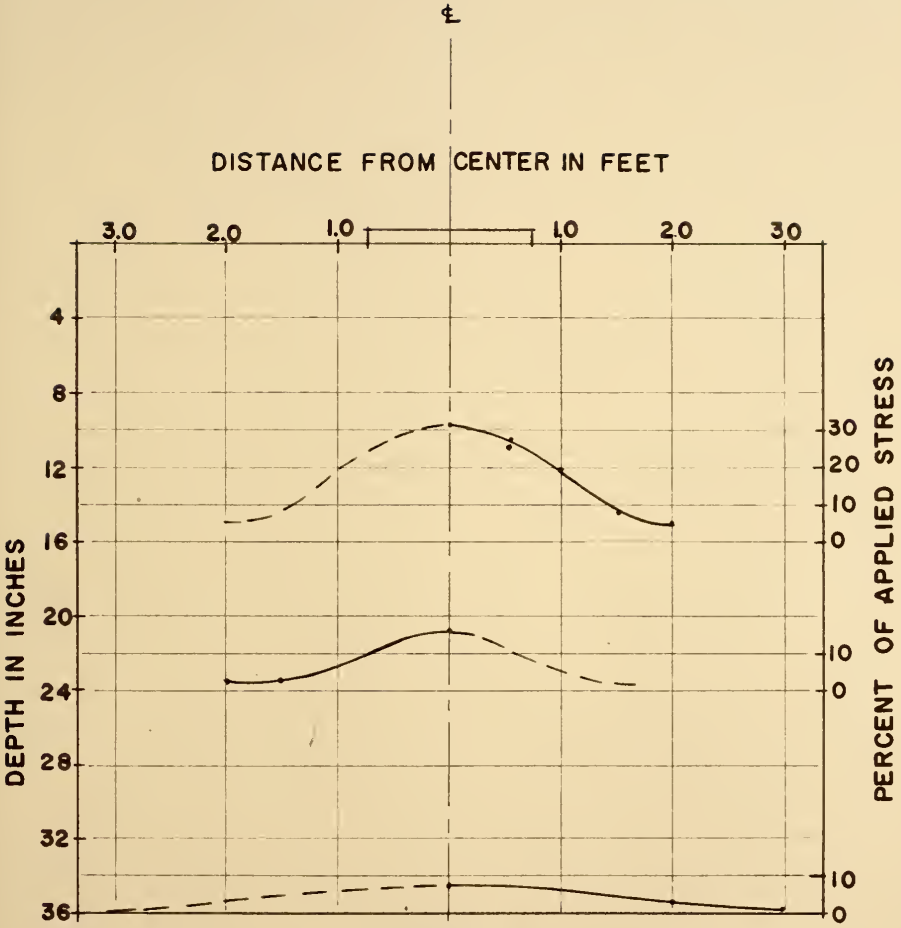


FIGURE 24
MEASURED PRESSURES
AS PERCENT OF APPLIED STRESS
18" DIAMETER PLATE
12" BASE MATERIAL
PRESSURE SCALE 1"= 40%

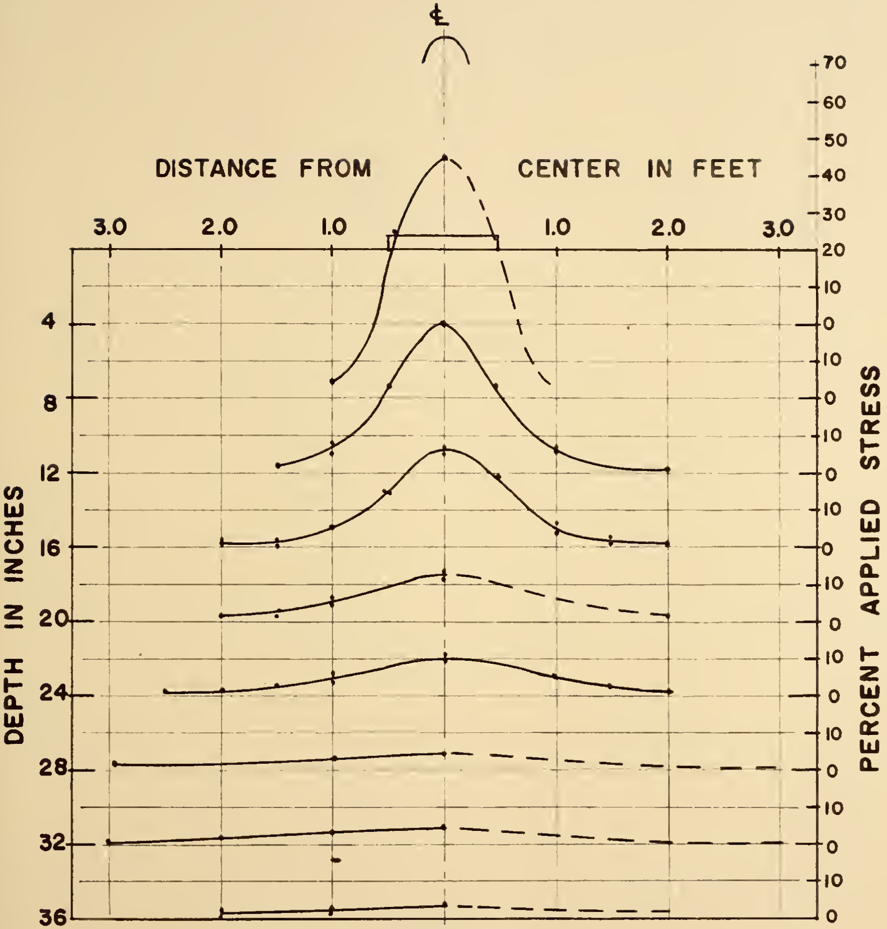


FIGURE 25
MEASURED PRESSURES
AS PERCENT OF APPLIED STRESS
12" DIAMETER PLATE
SUBGRADE ONLY
PRESSURE SCALE 1" = 40%

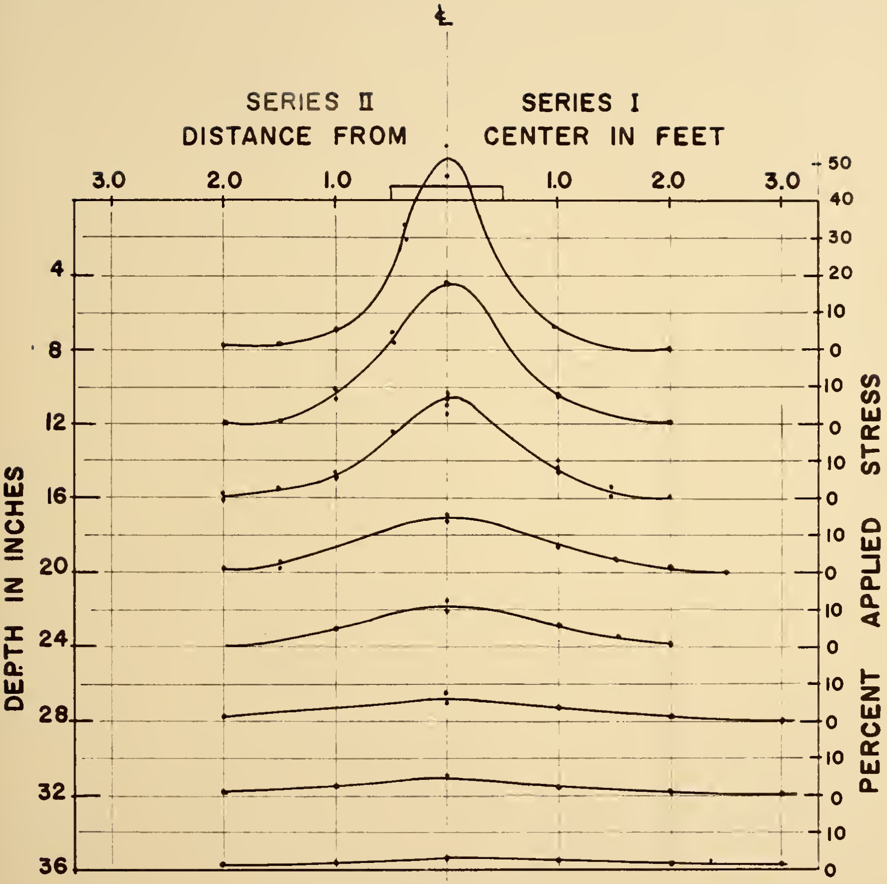


FIGURE 26
MEASURED PRESSURES
AS PERCENT OF APPLIED STRESS
12" DIAMETER PLATE
4" BASE MATERIAL
PRESSURE SCALE 1"=40%

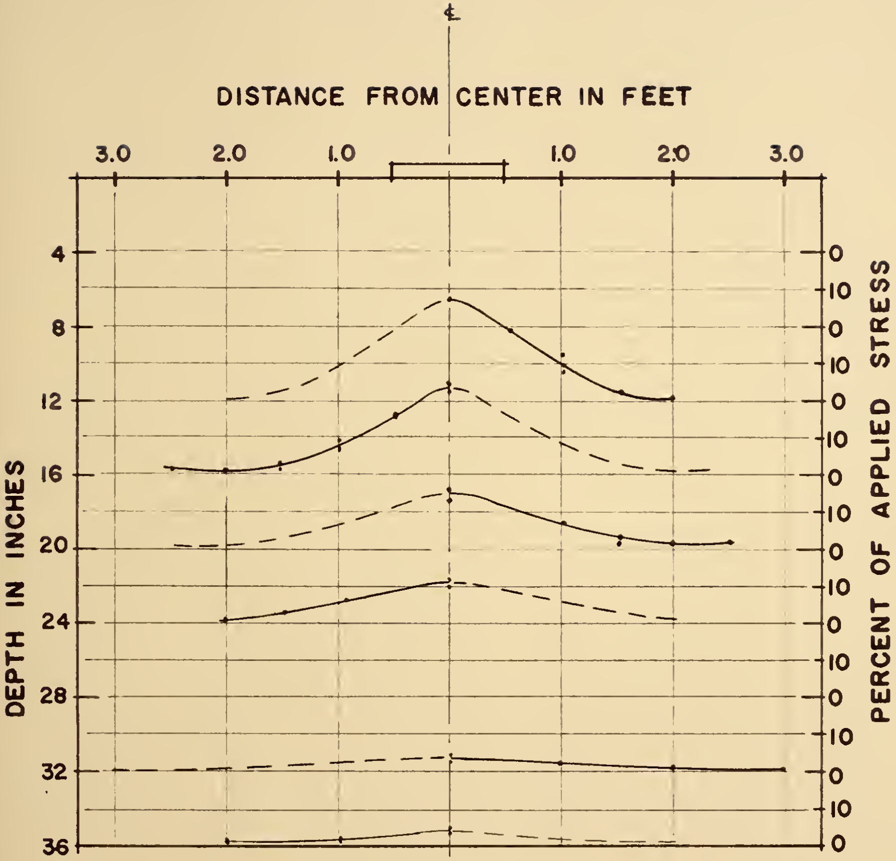


FIGURE 27
MEASURED PRESSURES
AS PERCENT OF APPLIED STRESS
12" DIAMETER PLATE
8" BASE MATERIAL
PRESSURE SCALE 1"=40%

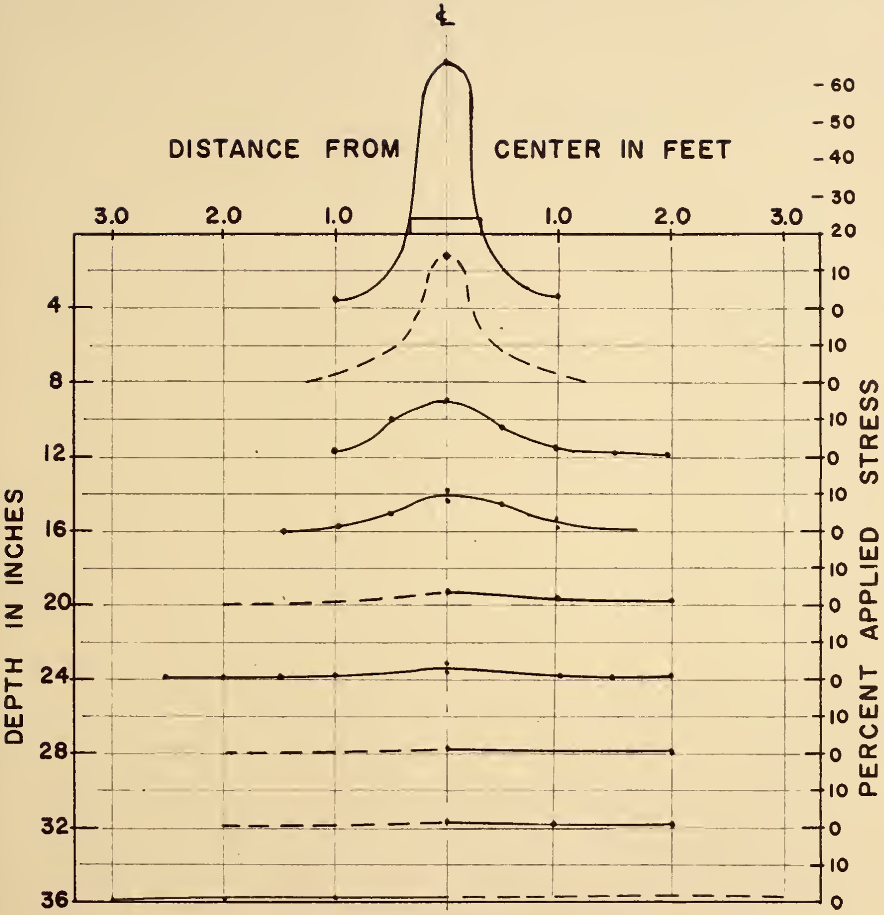


FIGURE 28
MEASURED PRESSURES
AS PERCENT OF APPLIED STRESS
$7\frac{3}{16}$" DIAMETER PLATE
SUBGRADE ONLY
PRESSURE SCALE 1"= 40%

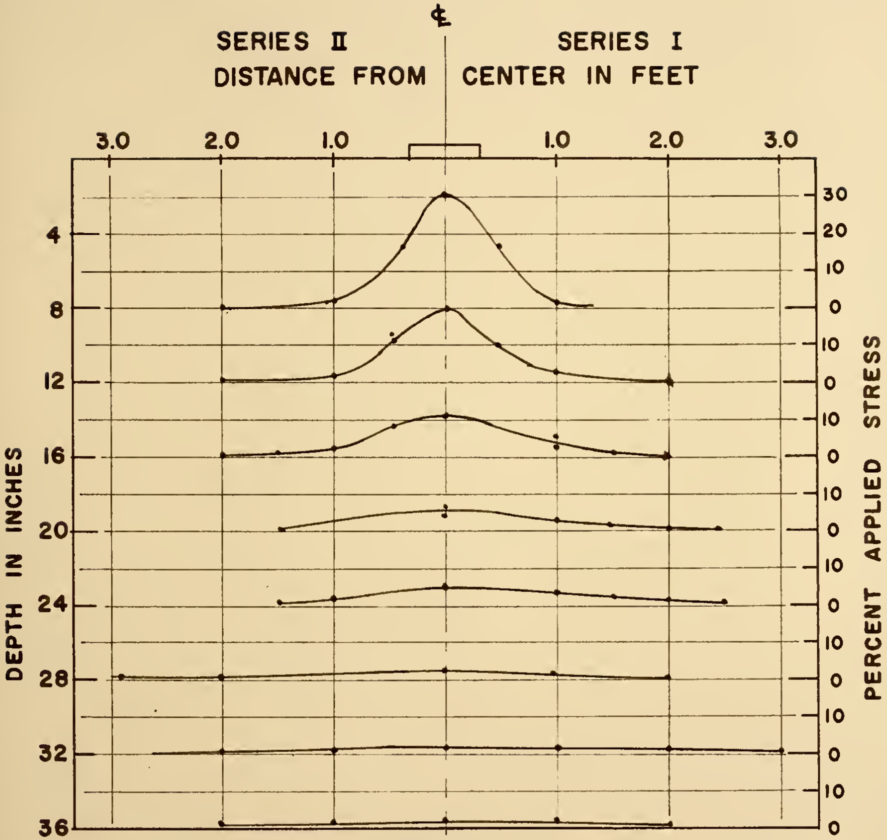


FIGURE 29
MEASURED PRESSURES
AS PERCENT OF APPLIED STRESS
$7\frac{3}{16}$" DIAMETER PLATE
4" BASE MATERIAL
PRESSURE SCALE 1" = 40%

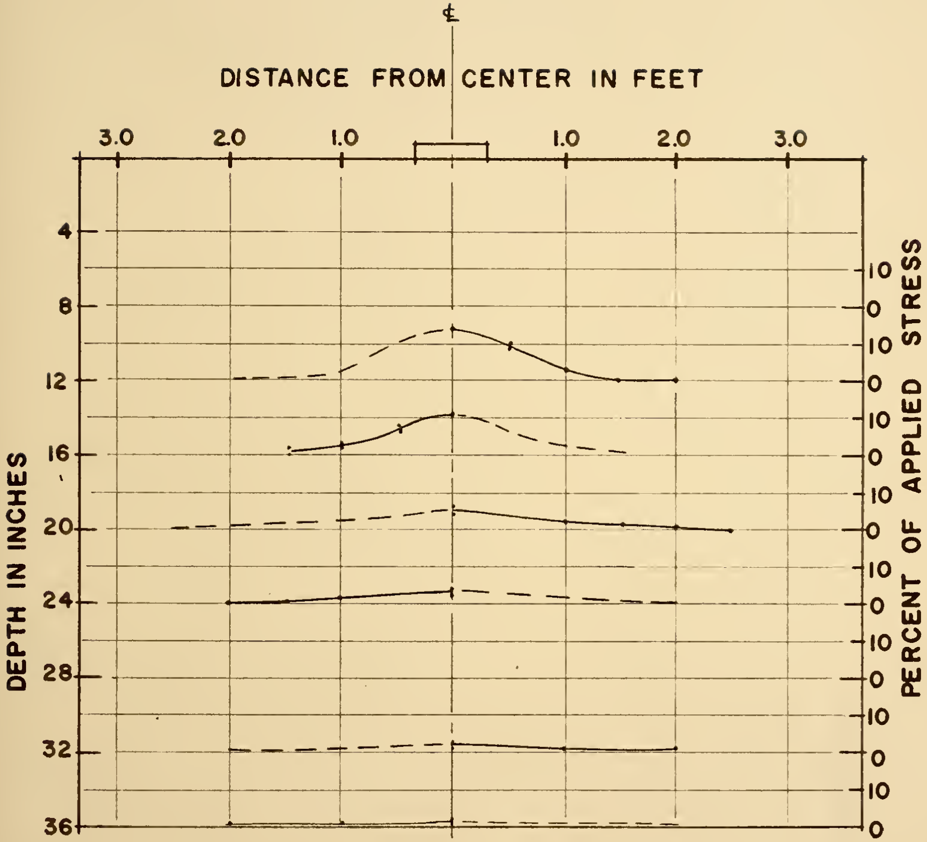


FIGURE 30
MEASURED PRESSURES
AS PERCENT OF APPLIED STRESS
7 3/16" DIAMETER PLATE
8" BASE MATERIAL
PRESSURE SCALE 1" = 40psi

However, these data have not been presented in curve form or included in the discussion. The data obtained was insufficient to be of value in the pressure distribution study.

Discussion of Results

The pressure distribution data obtained with the eighteen inch plate, in the four test conditions, are presented in Figures 21 to 24. A comparison of the curves in these figures indicates several trends in the data. There is a definite reduction in the measured pressures, at the shallower depths, as the base thickness is increased. However, the twelve inch base effects a reduction only slightly greater than that for the eight inch base. At the greater depths the base seems to have very little effect on the pressure distributions. A comparison of these curves with the curves of Figure 20, which are an adaptation of the curves presented by Foster and Ahlvin (16), delineates their departure from the theoretical. The curves for the homogeneous condition, Figure 21, are as much as 18 percent higher than the theoretical curves at the shallower depths, but are lower at the greater depths. This same trend is apparent in the pressures under the base courses in the other figures, except that near the interface the pressures seem to be less than the Boussinesq theory would indicate. It can be said, however, that the shapes of the curves, and even the magnitude of the curves, do not depart in a major sense from the Boussinesq theory. It must be remembered that the Boussinesq curves are for a uniformly loaded area, while the measured values relate to the distribution for semi-rigid plates used in the test. It would appear

from the curves that the pressure at the center of the plate, on the subgrade, was higher than the uniform pressure condition. However, according to the theory of elasticity the stress at the center of a rigid plate should be approximately one half of the uniform stress.

The distribution curves for the twelve inch and seven inch plates are presented in Figures 25 to 30. These curves exhibit the same general trend as do the curves for the eighteen inch plate. In order to ascertain the effects of the two series of tests on the results, where possible the data from Series I has been plotted on the right of the center line and that of Series II on the left. There is some difference in a few instances, but for the greater part not enough to affect the interpretation of the data. It is possible that with the weaker materials of Series I there has been more re-distribution of stress under the plate, resulting in a higher stress near the center.

In the comparison of the above curves, it is evident that the greatest differences occur near the centerline of the section, perpendicular to the center of the plate. In order to study these differences more thoroughly, the curves of Figures 31 to 34 have been prepared. These figures present the data for the pressures measured under the center of the plates at various depths for the four test conditions.

The curves of Figure 31 are representative of the pressures measured in the subgrade, under the centers of the three plates, for both series of tests. While there is a slight scattering of points, it is evident that the change in strength of the subgrade had very little, if any, effect on the measured pressures. A correlation of pressure with strength, as indicated by E values calculated from the load test

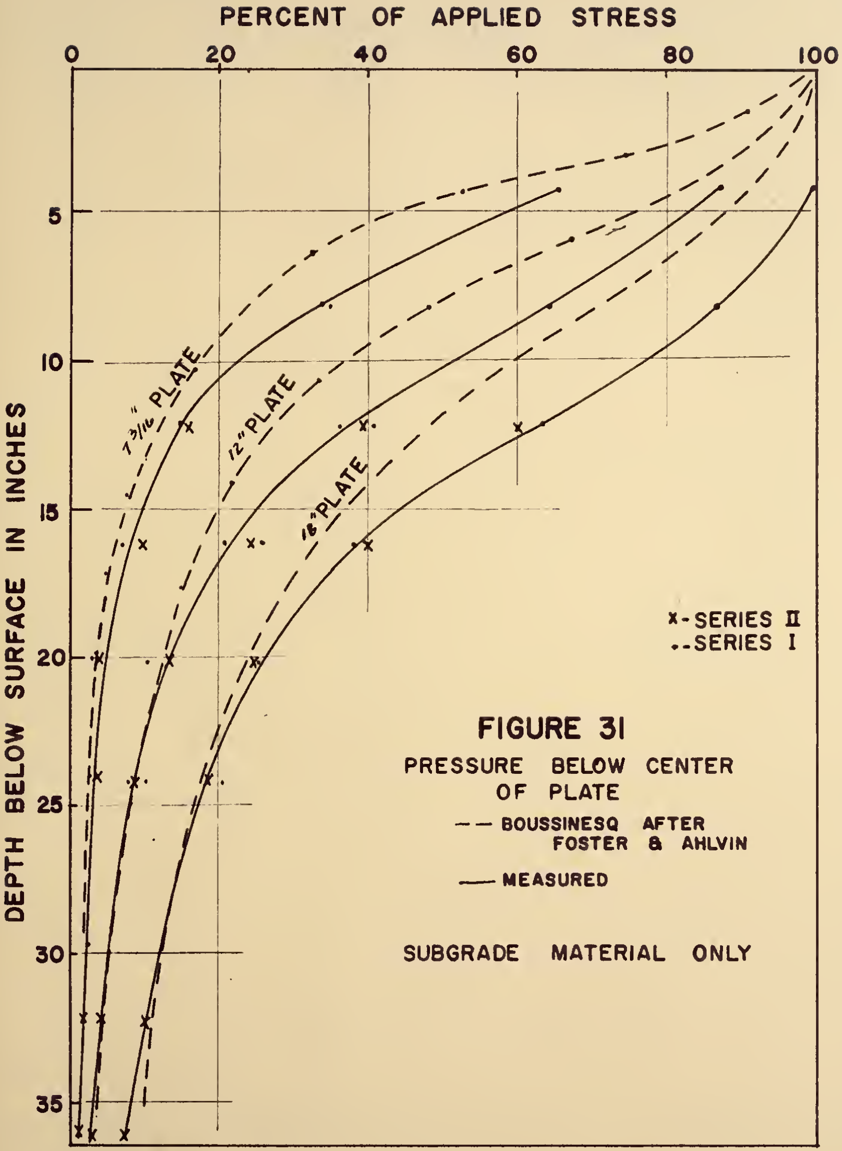


FIGURE 31

PRESSURE BELOW CENTER OF PLATE

SUBGRADE MATERIAL ONLY

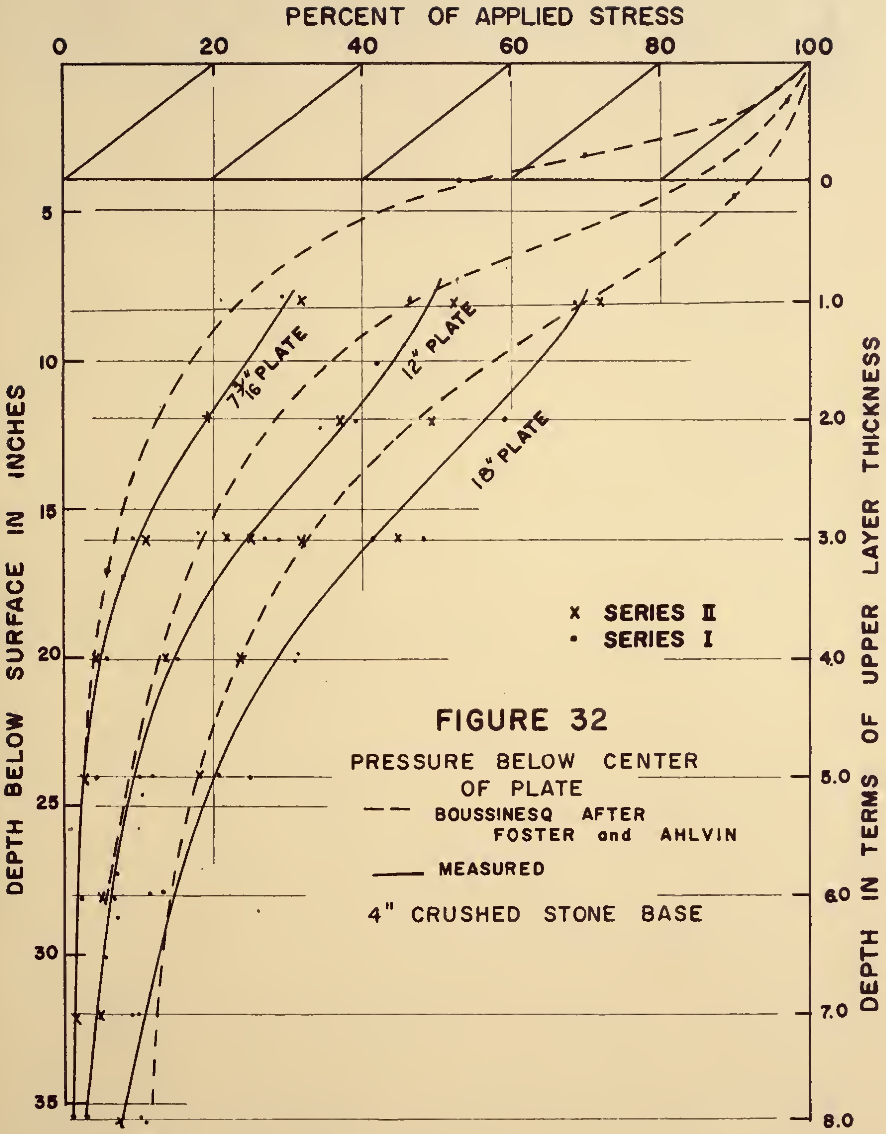


FIGURE 32

PRESSURE BELOW CENTER OF PLATE

4" CRUSHED STONE BASE

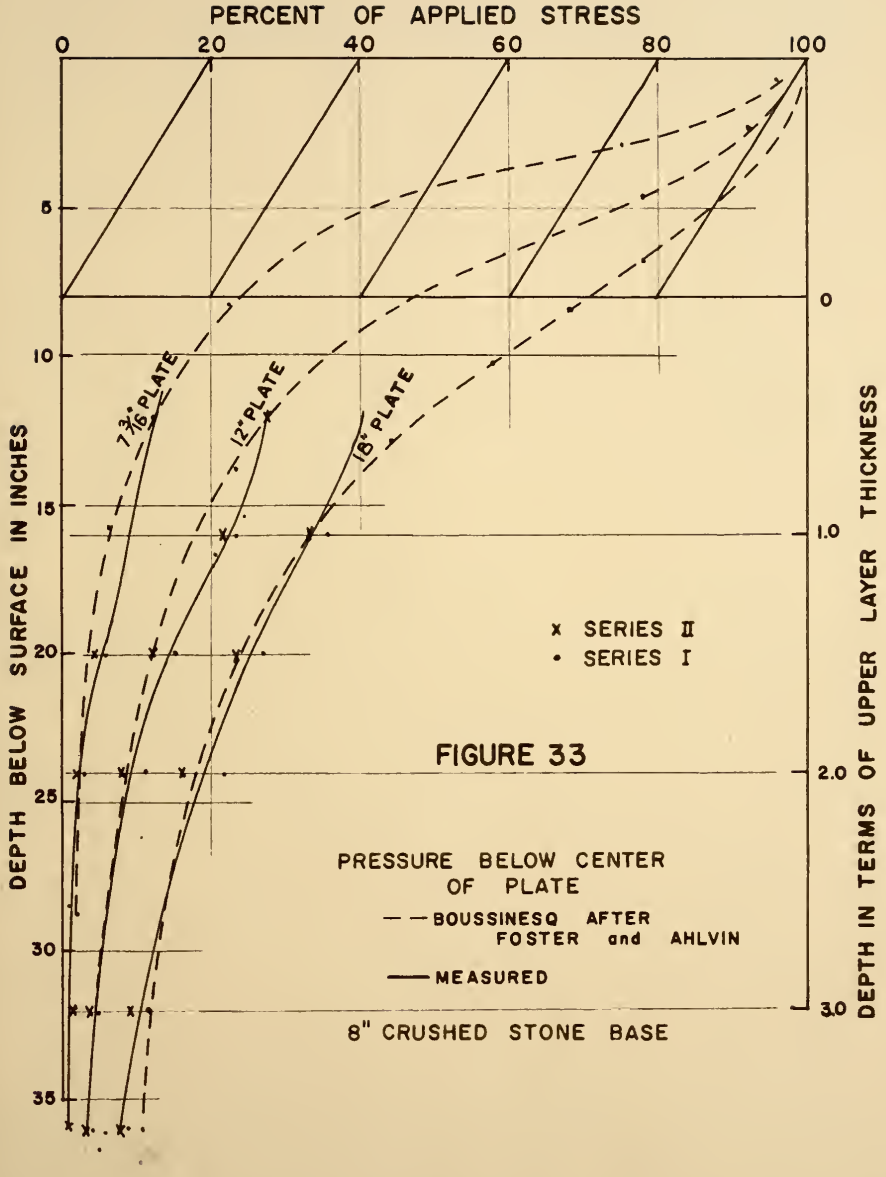


FIGURE 33

PRESSURE BELOW CENTER OF PLATE

8" CRUSHED STONE BASE

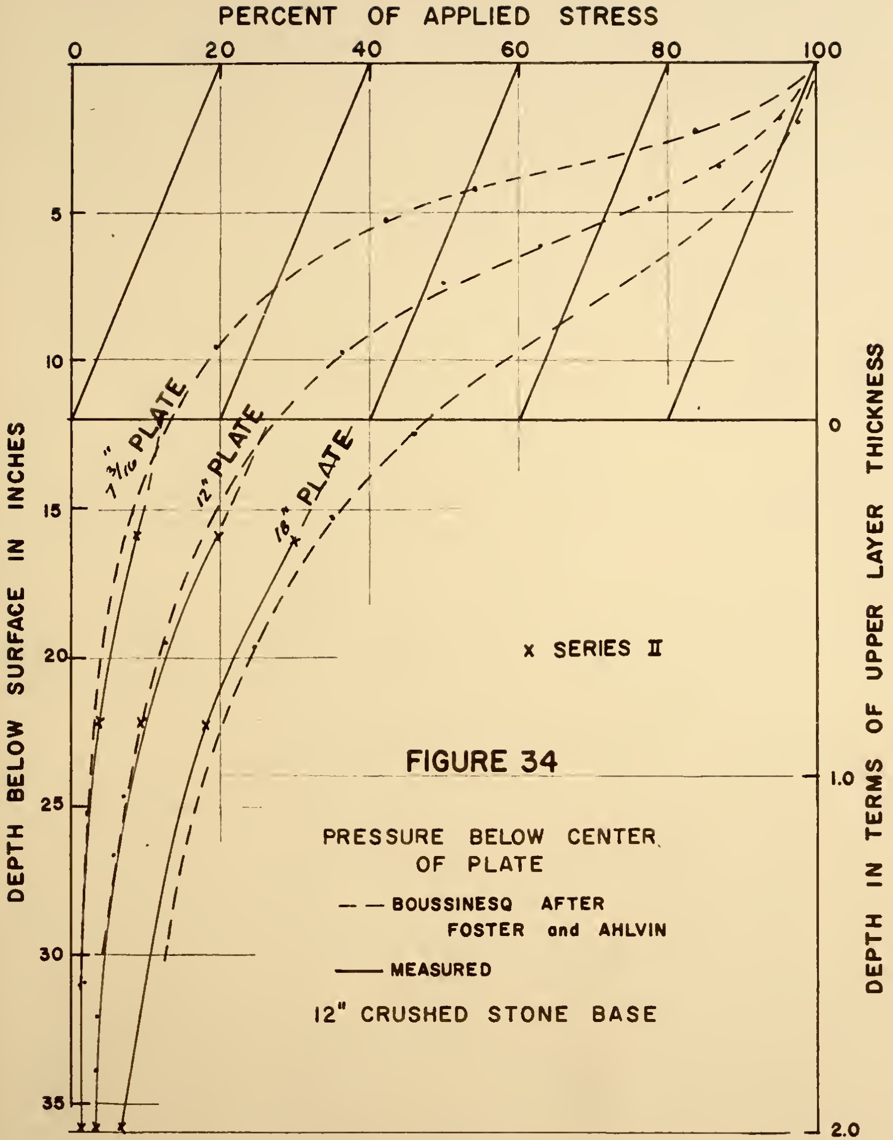


FIGURE 34

PRESSURE BELOW CENTER OF PLATE

12" CRUSHED STONE BASE

data, was attempted, but no definite trend could be established. There was, however, a slight indication that with the higher strength conditions the measured pressures tended to be lower. A range of E values from 400 to 1000 produces a variation of only two to five percent in the measured pressures. It is apparent that the measured pressures are considerably higher than the Boussinesq distribution for a uniform load, especially at the intermediate depths. The limited data available may produce an erroneous appearance here, but it would seem that the values at the center of the plate might be considerably higher than the average of the applied load, although this is contrary to theory. This would tend to produce the higher stresses in the upper areas, and the lower stresses with depth, that are depicted by these curves. All three plates behaved in a similar manner.

The curves of Figure 32 are drawn to best fit the available data, when the loaded plate rested on the surface of a four inch layer of crushed limestone base. In these curves it is evident that the strength of the base material plays an important part in the magnitude of the induced stresses. The calculated ratios, of the modulus E of the base to the modulus E of the subgrade, vary from one to fourteen. The pressure values measured under the weaker bases are higher than the values measured when the bases were stronger. This is shown quite well by the difference in the pressure measurements for Series I and Series II. It is also apparent that the strength relationships are much more critical for the larger plates. The points depicting the values obtained in Series II, under the eighteen inch plate, nearly coincide with the theoretical curve of Boussinesq for a uniformly

distributed load, while the points for Series I are not greatly different from the curve for the homogeneous condition. The data for the twelve inch plate is somewhat scattered, but the values obtained under the seven inch plate have not been affected. The values of all the curves are greater, over most of their length, than those of the theoretical curves, and in some places are even greater than for the homogeneous condition. However, near the bottom of the base the pressures seem to be considerably lower than the theoretical values.

The curves of Figure 33, for the eight inch base condition, exhibit much the same features as those for the four inch base condition. It can be seen that the values have been lessened and more nearly approach the theoretical values. Here again, as in the curves of Figure 32, there is a strong indication that the values near the interface are much less than in the homogeneous condition.

The curves of Figure 34 are for the limited data of the twelve inch base condition. They also exhibit the characteristics discussed in the four and eight inch base conditions. It is, however, evident that the percent decrease in pressure is less between the eight and twelve inch conditions than it was between the four and eight. This would substantiate the theory that the stresses in the subgrade approach those of the homogeneous condition as the ratio of the base thickness to the radius of the plate increases.

In Figures 35 to 37 the stress distributions under the center of each plate, for the four test conditions, are presented. Several important features of the stress distributions are indicated in these curves. For the plate sizes used in the investigation, the base

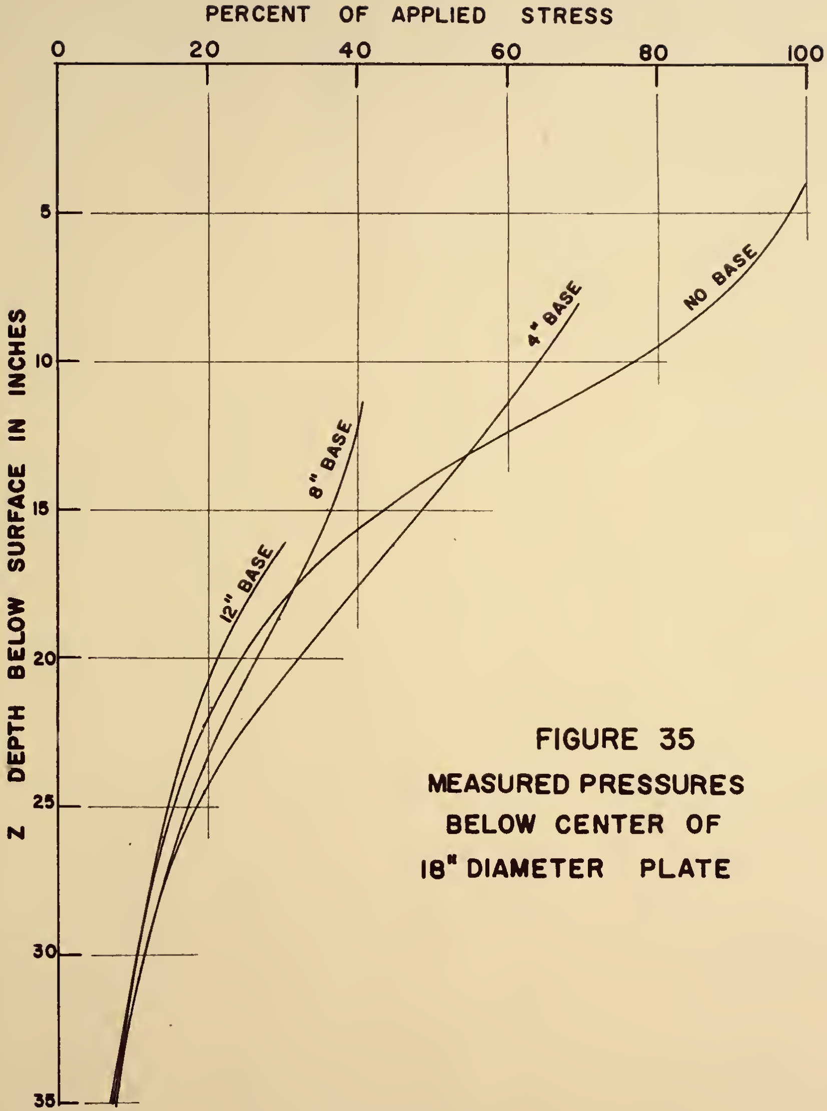


FIGURE 35
MEASURED PRESSURES
BELOW CENTER OF
18" DIAMETER PLATE

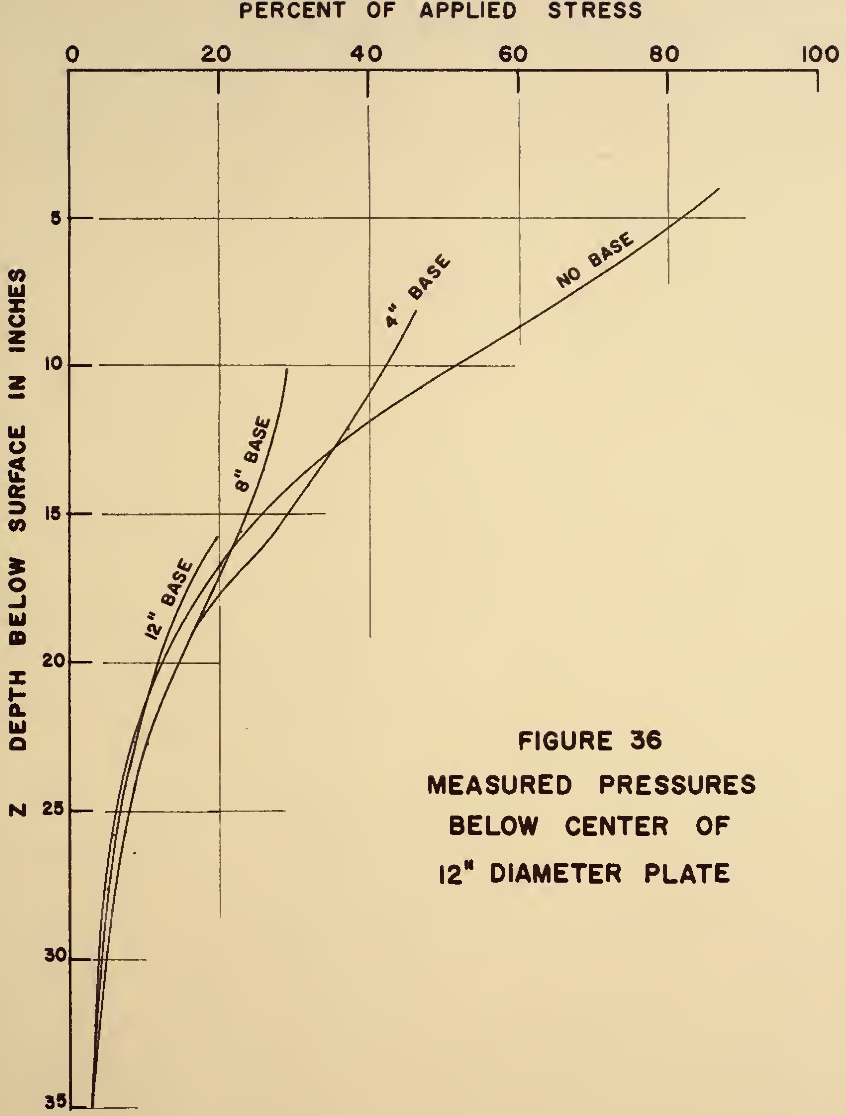


FIGURE 36
MEASURED PRESSURES
BELOW CENTER OF
12" DIAMETER PLATE

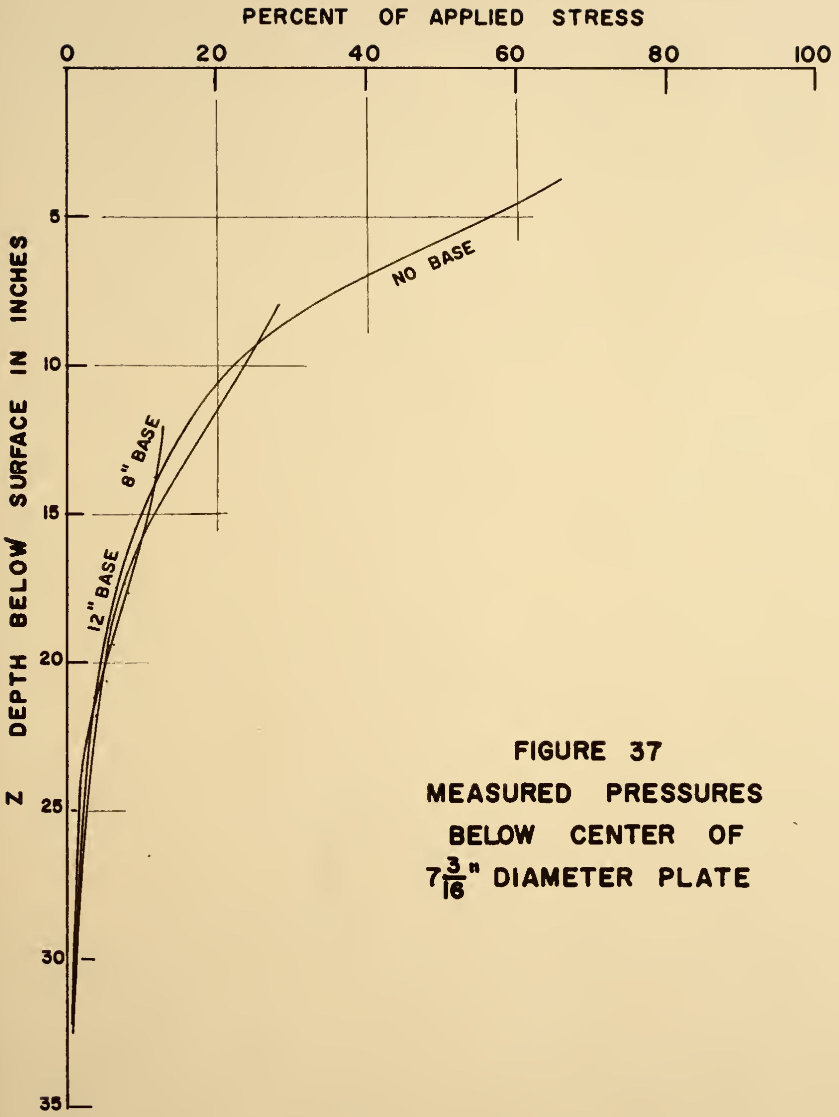
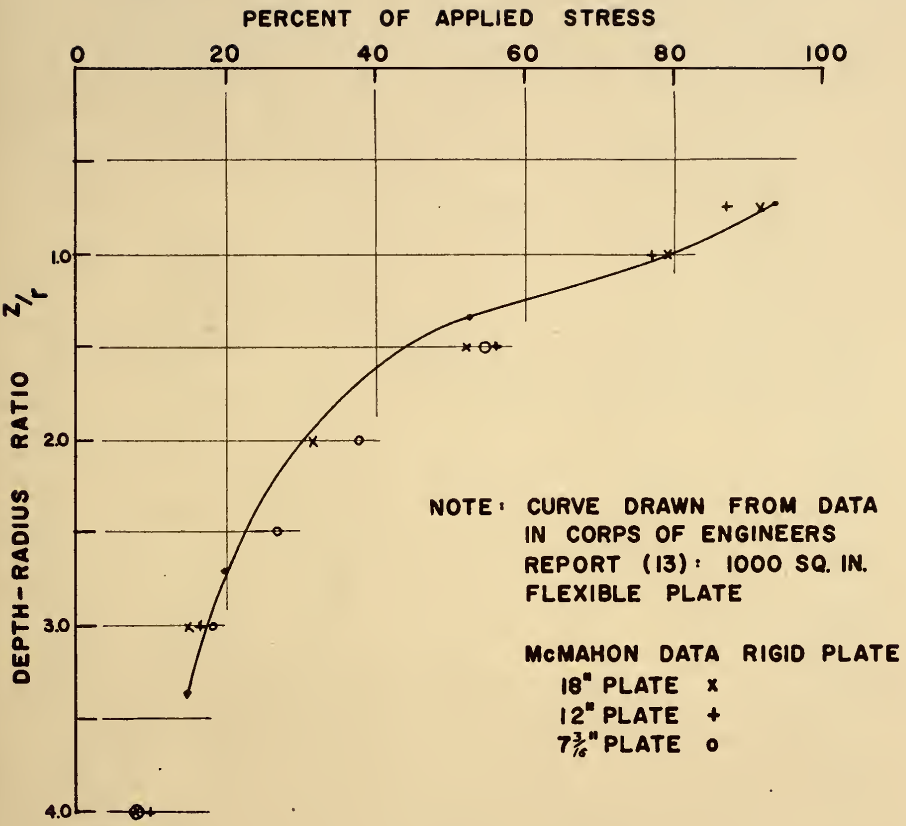


FIGURE 37
MEASURED PRESSURES
BELOW CENTER OF
$7\frac{3}{16}$" DIAMETER PLATE

thickness does not affect the magnitude of the pressures, to any great extent, below a depth of eighteen inches. The point that the base course affects stresses primarily at the base-subgrade interface is again noted. These curves also indicate an optimum base thickness for each plate size. It would seem that this thickness might be approximately equal to the radius of the plate. It is also evident that a thin, weak base may result in a failure condition at a depth below the surface instead of providing strength to the system.

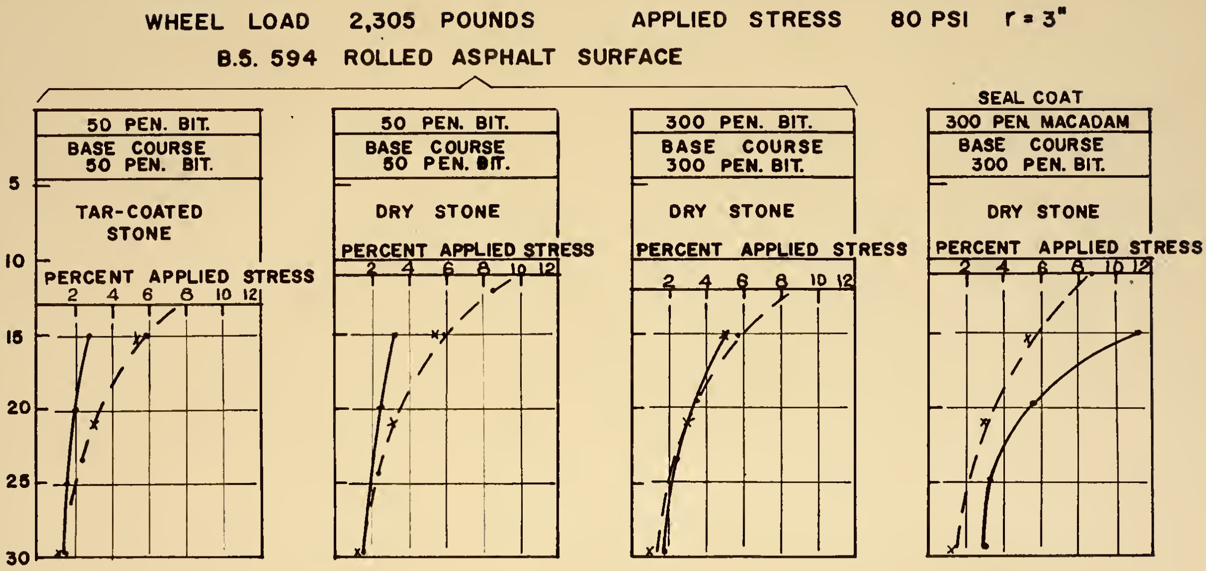
In Figure 38, data from a report published by the Corps of Engineers (13) is presented as a curve of stress distribution with depth. The points along the curve are data from this investigation. A correlation between the two sets of data exists in spite of the differences in the test conditions. The Corps of Engineers, in their investigation, used a one thousand square inch flexible plate to apply loads of much greater magnitude than were used in this study. The data from both investigations are for the homogeneous soil condition. The data from both projects have similar trends; namely, the values for both are higher than the theoretical values of Boussinesq, and both also indicate that the pressure under the center of the plate was higher than it would be for a uniform distribution, which is to be expected for the flexible plate.

English engineers have been making investigations of pressures beneath flexible pavements with some success. Figure 39 is a reproduction of a presentation from a report (14) on one of their projects, with the Boussinesq values for a uniformly loaded area, and values from this study reduced to Z/r terms, superimposed on it. This figure



NOTE: CURVE DRAWN FROM DATA IN CORPS OF ENGINEERS REPORT (13): 1000 SQ. IN. FLEXIBLE PLATE

FIGURE 38
COMPARISON OF MEASURED STRESSES
CORPS OF ENGINEERS AND McMAHON
UNDER CENTER OF PLATE
SOIL ONLY



NOTE: PAVEMENT SECTIONS AND SOLID LINE CURVES TAKEN FROM ENGLISH RESEARCH REPORT (14) MOVING WHEEL LOADS
DASHED LINE CURVES AFTER BOUSSINESQ
x FROM McMAHON DATA 12" BASE UNDER CENTER OF LOAD

FIGURE 39
COMPARISON OF MEASURED STRESSES
FISHER, LEE AND MILLARD AND McMAHON

also indicates the changes in pressure which occur with changes in strength of the upper layer.

In the previous discussion the comparisons of measured values with the theoretical values have been made using the Boussinesq theory for a uniformly loaded plate. In Figures 40 to 44 a comparison has been made of the values obtained in this investigation with values computed by L. Fox (17) using the Burmister Two-Layer Theory. This comparison has been made by methods described by D. M. Burmister (5). Figure 40 presents typical load-deflection curves from the load tests that were performed as the pressure measurements were made. These curves have been used to determine E_2, the modulus of the subgrade; E_1, the modulus of the combined system; and F_w, Burmister's strength coefficient. The calculated value of F_w is used in the chart of Figure 41 to determine the value of E_2/E_1, the ratio of the modulus of the lower layer to the modulus of the upper layer. Figures 42 to 44 present the comparable data of this investigation and the theoretical curves as established by Fox. The data for the tests of Series II have been used for this comparison as the modulus ratio for this data was near or above the 1/10 ratio used by Fox. A perfectly rough interface was assumed in the computation of the Fox values. It is evident that the values obtained in this investigation are considerably higher than those computed by the Burmister Two-Layer Theory. However, as the strength of the base was so low, it was felt that this comparison was questionable.

The test data suggest that the effect of the base course in reducing stresses is primarily at the base-subgrade interface. Thus

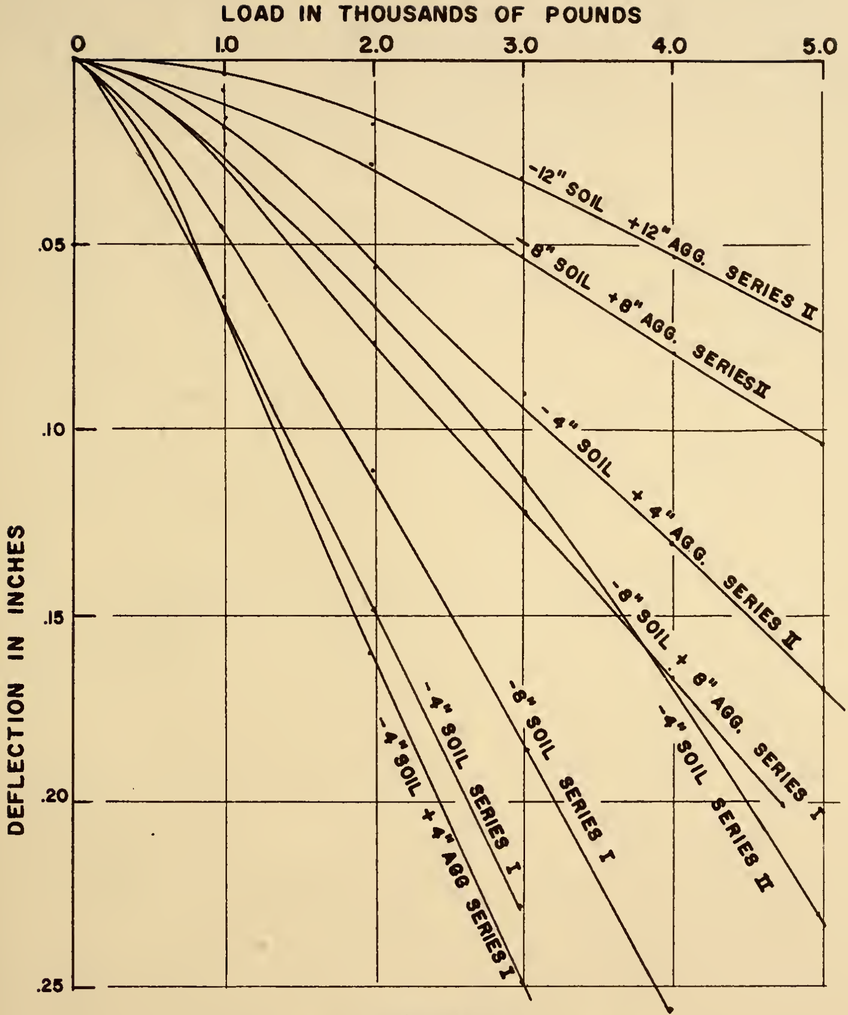
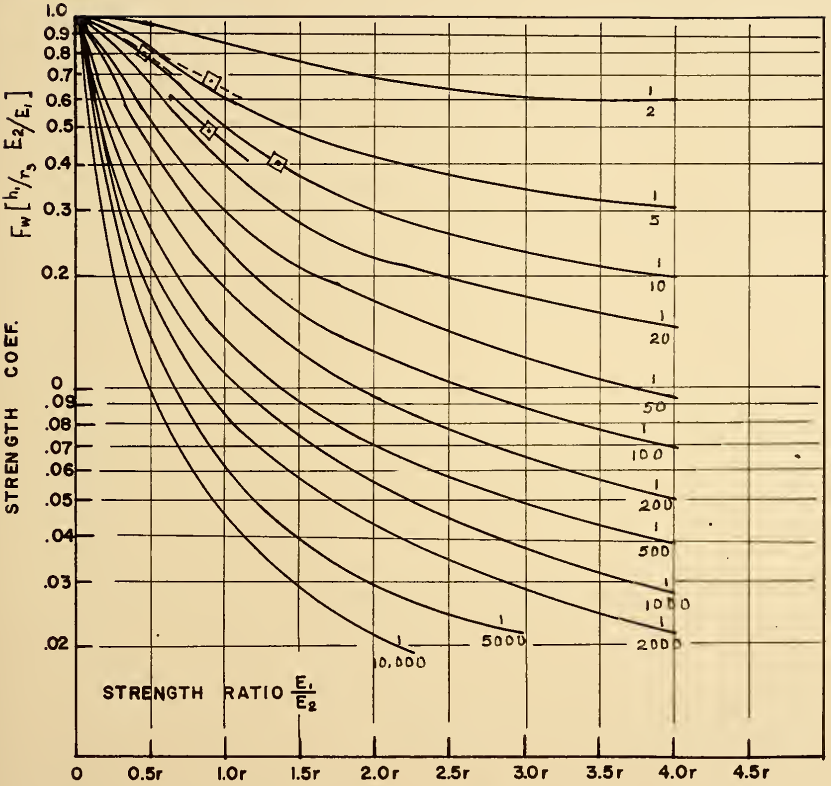


FIGURE 40
LOAD-DEFLECTION CURVES
18" DIAMETER PLATE

FIGURE 41

BURMISTER INFLUENCE CHART



THICKNESS- h OF REINFORCEMENT LAYER
EXPRESSED AS MULTIPLES OF THE RADIUS OF BEARING AREA

FROM BURMISTER
TWO LAYER SOIL PROBLEM 1943

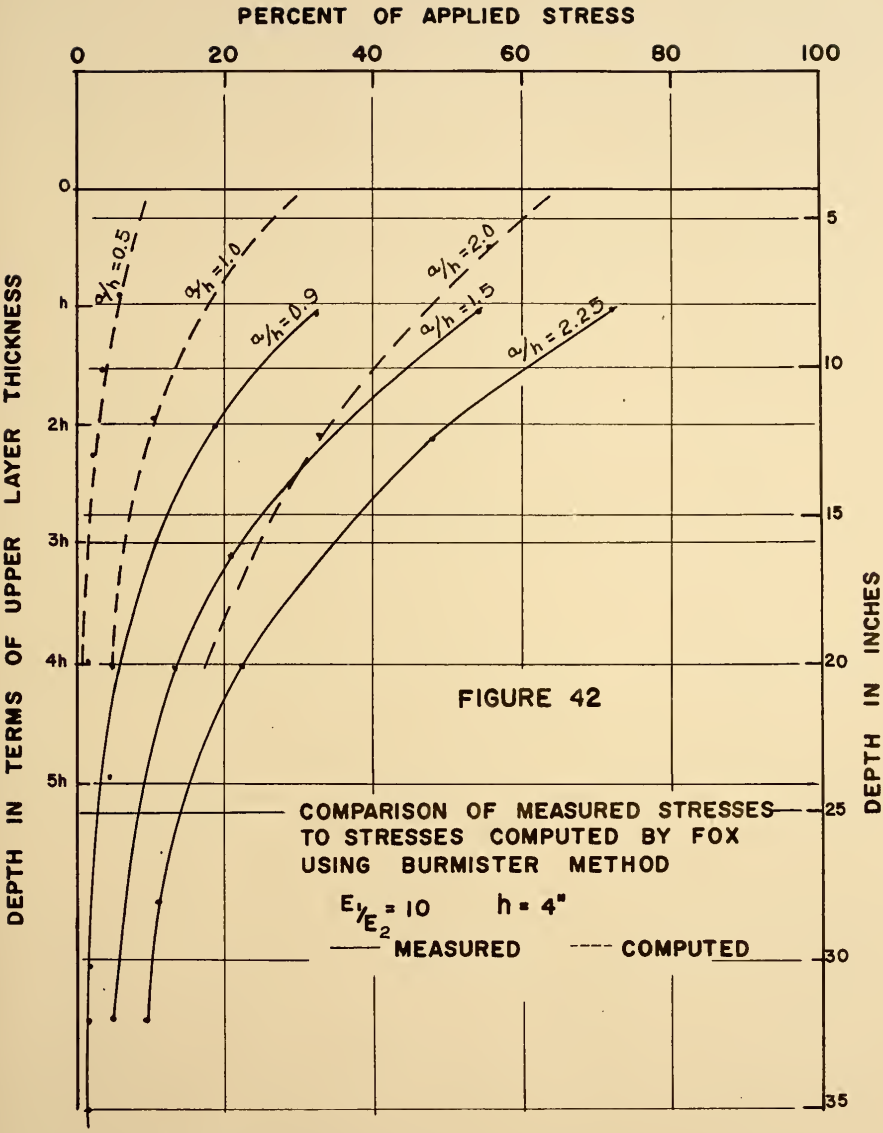


FIGURE 42

COMPARISON OF MEASURED STRESSES TO STRESSES COMPUTED BY FOX USING BURMISTER METHOD

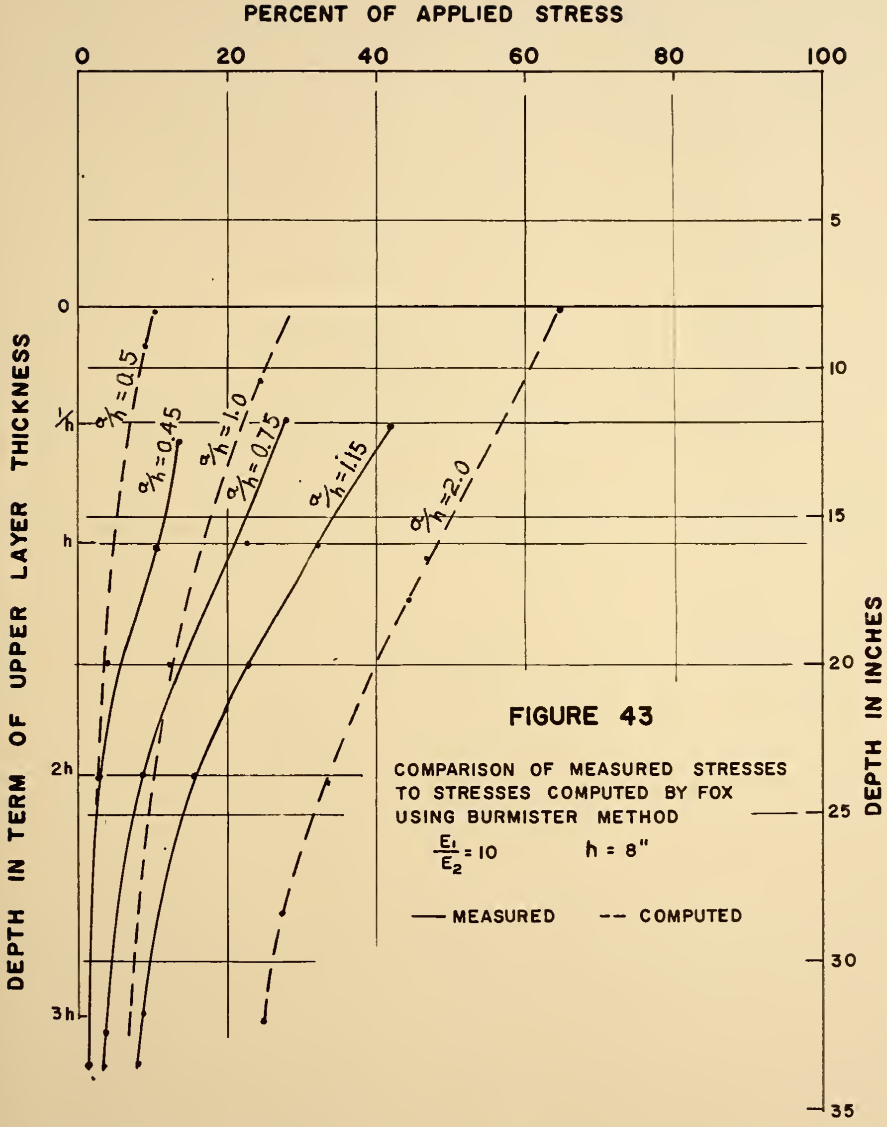


FIGURE 43

COMPARISON OF MEASURED STRESSES TO STRESSES COMPUTED BY FOX USING BURMISTER METHOD

$\frac{E_1}{E_2} = 10$ $h = 8''$

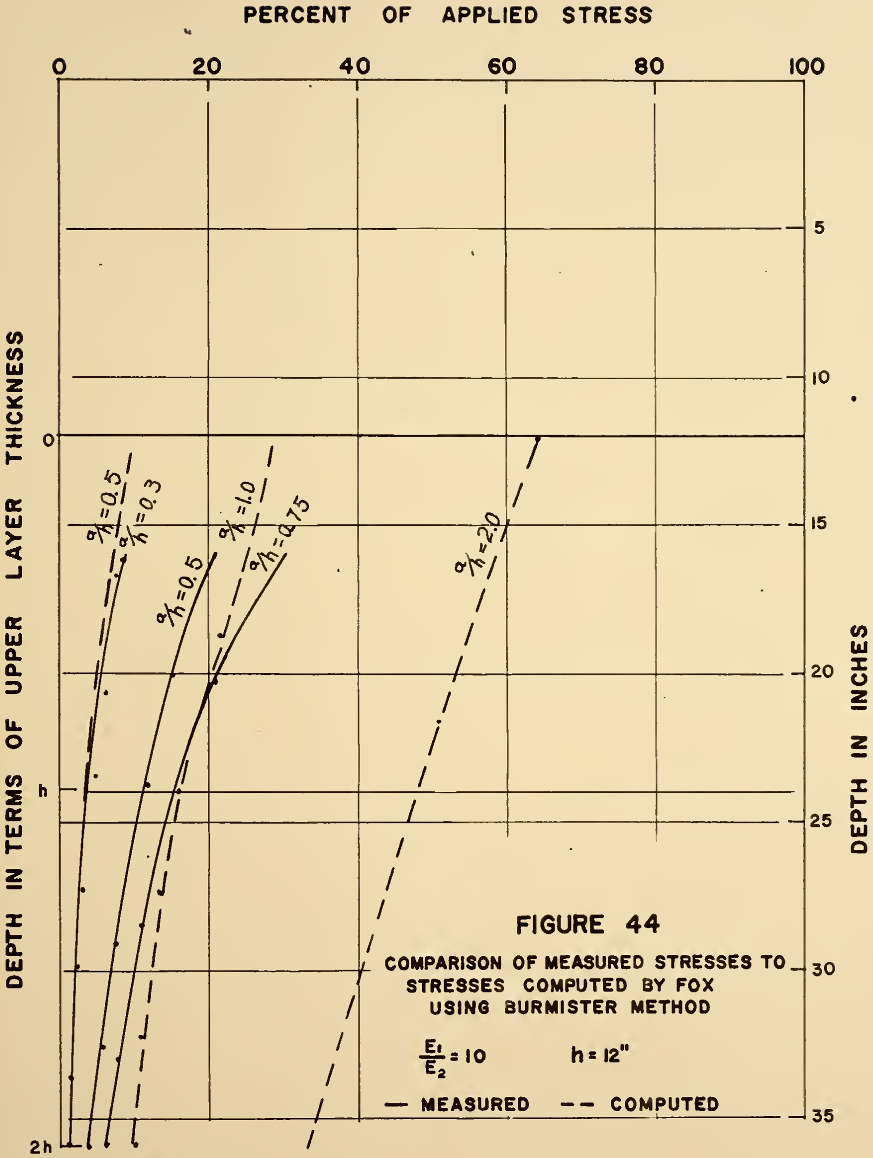


FIGURE 44

COMPARISON OF MEASURED STRESSES TO STRESSES COMPUTED BY FOX USING BURMISTER METHOD

$\frac{E_1}{E_2} = 10$ h = 12"

it would be reasonable to assume that the stresses below the base follow the theoretical values if the true stresses at the interface were used as the surface pressure. To test this hypothesis the curves of Figure 32 and 33 are again presented in Figures 45 and 46. Upon these figures are superimposed points of stress that have been calculated by an Equivalent Plate Method. These points have been determined in the following manner: First, the curves of the measured pressures were extended to intersect with the interface of the system. It was then assumed that this intercept was the average percent of applied stress on a plate, composed of a circular section of the base, of a size to have a uniform stress of this magnitude. The points were then calculated, using the charts of Foster and Ahlvin (16). It is evident from the figures that there is a marked similarity between the results of this method and those of the investigation. It is also evident, from the figures, that this stress is somewhat higher than the actual uniform stress on a plate of this size at this position. This feature is made evident by the departure of the points from the Boussinesq distribution at the greater depths. However, the curves represent measured data, and therefore may not be representative of a uniform stress on a plate. The curves of Figure 31 indicate that the stresses at the center of a plate on a clay-soil subgrade are greater than the average applied stress. The work of the Civil Aeronautics Administration (2) also indicate that the stress transmitted to the subgrade, through a base, is considerably higher in the central zone of the affected area. With this factor in mind, it is not unreasonable to assume that the measured stresses near the interface will be higher than would be

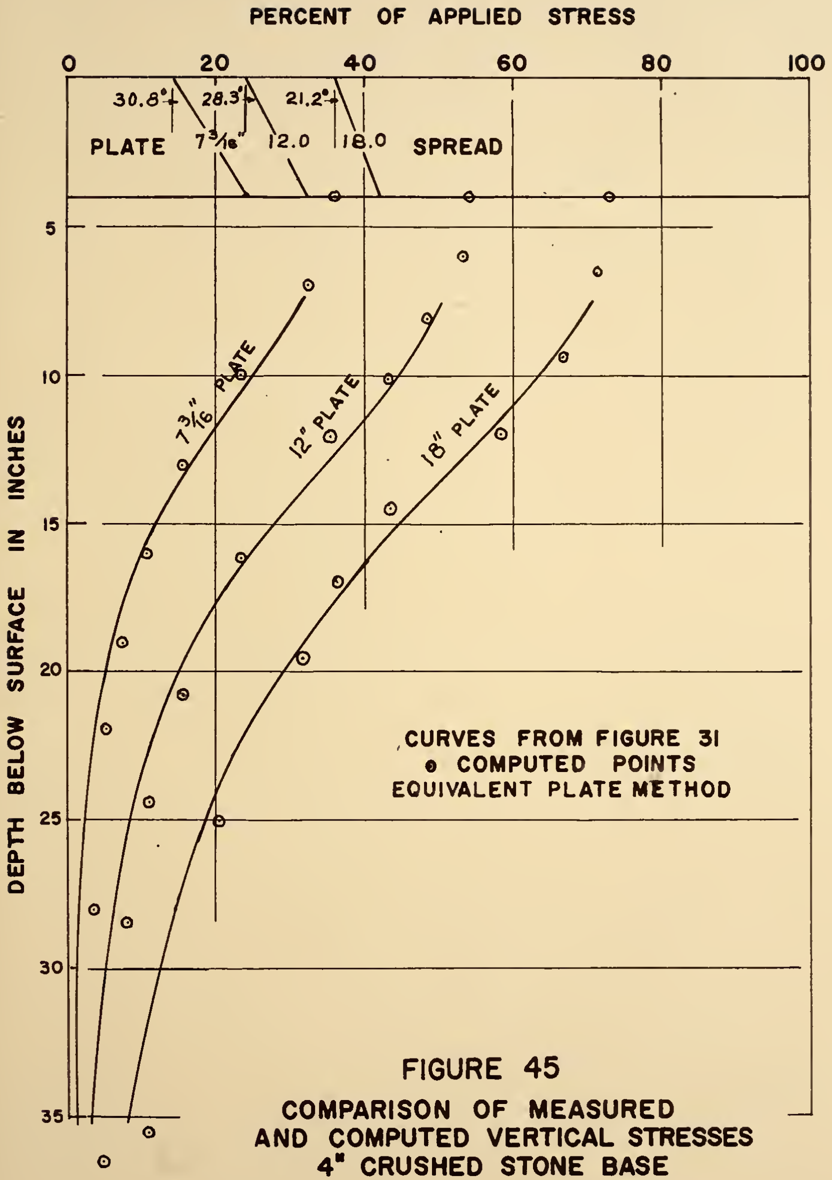


FIGURE 45

COMPARISON OF MEASURED AND COMPUTED VERTICAL STRESSES 4" CRUSHED STONE BASE

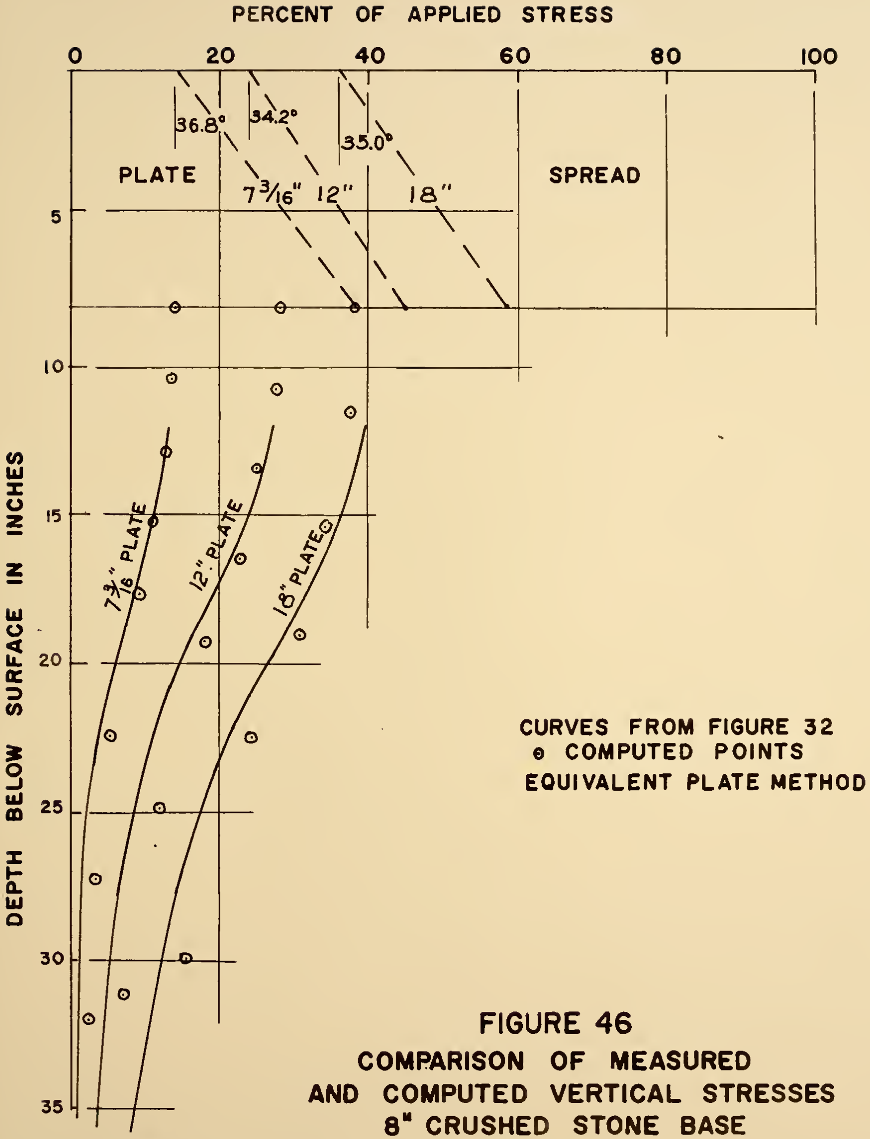


FIGURE 46
COMPARISON OF MEASURED
AND COMPUTED VERTICAL STRESSES
8" CRUSHED STONE BASE

commensurate with a uniform distribution. It is possible that, if the calculated points were made to fit the lower portion of the theoretical curve, the intersection of the calculated curve with the interface would indicate the true magnitude of a uniform pressure over an equivalent plate.

It is also apparent from the figures that the spreading of the load is not a constant for all conditions of the base material. It is evident that the strength of the base course influences the spread of the load. The angle of spread determined for the eighteen inch plate on the four inch base is only 21.2 degrees. The modulus calculated for this material, Tables 24 and 25, is even less than that for the soil alone. The spread angles, of 28.3 and 30.8 degrees, for the twelve inch and seven inch plates respectively, can be explained by the sequence of loading used during the testing. The eighteen inch plate was applied first. This resulted in a compaction and a strength increase in the base, which is reflected in the spread angles of the smaller plates. The spread angles for the eight inch base are reasonably uniform. The data of the twelve inch base was not considered to be adequate for a like analysis. However, the spread effect, as calculated for the seven inch plate, is 43 degrees.

SUMMARY

Results

The major findings of the research may be summarized under topical headings of the various phases of the investigation in the following manner.

Design and Development of a Pressure Cell

A pressure cell was designed and developed as a portion of this study. The available literature was studied to ascertain the extent of the knowledge of the design of a cell and its limitations in use. The design was based on the criteria established by the Corps of Engineers, using the theory of elasticity to calculate the required dimensions.

The cell was tested to establish its behavior characteristics in air, clay, and sand media. It was determined that the functioning of the cell in the air was very similar to that in the clay medium.

The cell was also inserted in several clay-soil triaxial specimens and the measured stresses compared with theoretical stresses computed by the Mohr Circle method. It was determined that the degree of accuracy of the cell, as delineated by this comparison, was in all cases within an accuracy of plus or minus five percent, and usually much less.

Laboratory Pressure Cell Measurements

Two series of pressure measurement tests, involving seventeen separate loading conditions, were made in an 18 x 18 x 18 inch box, under loads applied with a 5-1/4 inch diameter plate. Measurements were made within homogeneous systems and within layered systems.

The stress pattern, formed by the measured pressures appeared to follow the theoretical pattern of Boussinesq. However, the magnitude of the measured stresses deviated from the computed values. In a homogeneous system the stresses were smaller, and in a layered system larger, than those predicted by the Boussinesq theory. It was felt that the side effects of the small box were significant and that arching effects, within the homogeneous mass, were contributing to the reduction in the measured values.

Field Pressure Cell Measurements

Two series of field pressure measurement tests, involving fifty-three separate loading conditions, were made in an 8 x 8 foot model. Three plate sizes were used in these series of tests, 7-3/16, 12, and 18 inches in diameter. Tests were performed with homogeneous systems and with two-layer systems. In the two-layer systems, 4, 8, and 12 inches of the homogeneous material were replaced by the same thickness of crushed stone base material. The results of these tests were compared with values calculated by known theories.

The pattern, depicted by the field measurements, again followed the Boussinesq theory for a uniformly distributed load in form. However, with the elimination of the side effects, the measured pressures

were greater in magnitude than the computed values, in both the homogeneous and the two-layer systems.

The base, in the two-layer systems, appeared to act as a load spreading medium. There was a definite reduction of stress in the zone directly below the base-soil interface. However, this reduction became negligible within a distance of r or less below the interface and the measured pressures again became higher than the theoretical values of Boussinesq for a uniformly loaded area. The measured pressures at intermediate depths were even higher than they were for the homogeneous condition.

A comparison was made between the measured pressures and the corresponding stresses computed by the Burmister theory under the center of the plates. The Burmister values were definitely lower than those that were measured in this investigation. However, the pattern of the measured distribution, near the interface, is similar to that predicted by Burmister, but at the greater depths it does not show a compatible reduction in stress. However, the low values of E of this investigation made it difficult to compare these distributions.

Calculations were made of the stresses which would be induced in the subgrade, by a plate, having a uniform load and an area compatible with the stress indicated at the interface, by an extrapolation of the curves of measured pressure. This plate was positioned at the interface and used as an equivalent area of base material. The calculated values, determined by the Boussinesq theory, correlated very well with the measured values.

Conclusions

The major conclusions drawn from the experimental results may also be summarized under pertinent topical headings.

Design and Development of a Pressure Cell

The pressure cell, which was designed and developed as part of the investigation, measured the pressures within the subgrade with a high degree of accuracy. The values measured by the cell in the triaxial tests indicated that the true values may be slightly lower than the measured values.

Field Pressure Cell Measurements

Conclusions have been drawn for the two types of systems tested. The conclusions pertaining to the homogeneous system are:

1. Stress distributions within a homogeneous soil mass, under the conditions of this investigation, resemble the Boussinesq distribution, but are higher in magnitude at the shallower depths at the centerline.

2. The stress distribution, within a homogeneous soil mass, is affected but very little by a considerable change in the strength of the mass.

3. There was little discrepancy between the pressures measured under a flexible plate by the Corps of Engineers and under the more rigid plates of this investigation.

The conclusions pertaining to the two-layer system are:

1. The effect of the base course was noticed primarily at the interface of the base and the subgrade. However, as the

ratio of z/r increases, this effect becomes less pronounced, approaching the theoretical values for a uniform system.

2. The stress distribution in a two-layer system depends, to a large degree, upon the strength of the upper layer.

3. In so far as the reduction in stresses is concerned, there is an optimum base thickness for each size of loaded area.

4. The stresses measured under moving loads, by English investigators, were of the same order of magnitude as those measured in this study.

RECOMMENDATIONS FOR FURTHER RESEARCH

There is much need for further research in the area of stress distribution and pavement design. Many factors must be evaluated before a rational method of pavement design can be evolved.

1. A careful study of the Burmister Two-Layer Theory should be made, with further comparison of measured data.

2. A study of the pressure distributions over the surface of both flexible and rigid plates is needed.

3. The effect of the strength of the upper layer and of the combined strength of both layers should be studied further.

4. A complete study of shear stress distributions and their importance in pavement design is needed.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. Ahlvin, R. G., "Waterways Experiment Station Large Triaxial Apparatus." Highway Research Board Bulletin 141, 1956. p. 19

1a. Aldous, W. M., "A Preliminary Evaluation of Load Transmission Data." Proceedings, Association of Asphalt Paving Technologists, Vol. 20, 1951.

2. Aldous, W. M., M. H. Price, and W. L. Shearer, Jr., "The Load Transmission Test for Flexible Paving and Base Courses, Part III." Civil Aeronautics Administration Technical Development Report No. 203, June, 1953.

2a. Balla, A., "Stress Conditions in the Tri-Axial Compression Test." Proceedings of the Fourth International Soil Mechanics and Foundation Engineering Conference, London, 1957. p. 140

3. Benkelman, A. C., and R. J. Lancaster, "Some Important Considerations in the Design and Use of Soil Pressure Cells." Public Roads Vol. 21, No. 12, Feb. 1941. p. 235

4. Boussinesq, J., "Application Des Potentials a Petude De L'equilibre et du Mouvements des Solids Elastiques." Gauthier-Villars, Paris, 1885.

5. Burmister, D. M., "Theory of Stresses and Displacements in Layered Systems." Highway Research Board Proceedings, Vol. 23, 1943. p. 126

6. Burmister, D. M., "Influence Values for Certain Stresses and Displacements in Layered Soil Systems." Journal of Applied Physics, Vol. 16, Part 2, p. 89; Vol. 16, Part 3, p. 126; Vol. 16, Part 5, p. 296, 1945.

7. Burmister, D. M., "Evaluation of Pavement Systems of the WASHO Road Test by Layered System Methods." Highway Research Board Bulletin 177, 1956.

8. Carlson, R. W., "Five Years Improvement of the Elastic Wire Strain Meters." Engineering News-Record, Vol. 114, No. 20, May 16, 1935.

9. Cooper, A. W., C. E. VandenBerg, H. F. McColly, and A. E. Erickson, "Strain Gage Cell Measures Soil Pressure." Agricultural Engineering, April, 1957.

10. Corps of Engineers, U. S. Army, "Soil Pressure Cell Investigation, Interim Report." U. S. Waterways Experiment Station, Vicksburg, Mississippi, 1944.

11. Corps of Engineers, U. S. Army, "Pressure Cells for Field Use." U. S. Waterways Experiment Station, Vicksburg, Mississippi, 1955.

12. Corps of Engineers, U. S. Army, "Stresses Under Moving Vehicles, A Pilot Study of WES Earth Pressure Cell Action in Comparatively Soft Soil." U. S. Waterways Experiment Station, Vicksburg, Mississippi, 1957.

13. Corps of Engineers, U. S. Army, "Investigations of Pressures and Deflections for Flexible Pavements, Report No. I." U. S. Waterways Experiment Station, Vicksburg, Mississippi, 1951.

14. Fisher, John McNeal, Alfred Robert Lee, and Raymond Spencer Millard, "Research and Its Application to Road Construction." The Institute of Civil Engineers, London, England, 1959. p. 495

15. Foster, C. R., and S. M. Fergus, "Stress Distribution in Homogeneous Soil." Highway Research Board, Research Report No. 12 F, Jan. 1951. p. 1

16. Foster, C. R., and R. G. Ahlvin, "Stresses and Deflections Induced by a Uniform Circular Load." Highway Research Board Proceedings, Vol. 33, 1954.

17. Fox, L., "Computation of Traffic Stresses In a Simple Road Structure." Road Research Laboratory, Technical Paper No. 9, Harmondsworth, England, 1948.

18. Froehlich, O. K., "Drukverdeeling Im Bouwground." De Ingenieur, April 15, 1932.

19. Goldbeck, A. T., and E. B. Smith, "An Apparatus for Determining Soil Pressures." American Society for Testing Materials, Proceedings, Vol. 16, 1916. p. 309

20. Goldbeck, A. T., "Distribution of Pressures Through Earth Fills." American Society for Testing Materials, Proceedings, Vol. 17, Part 2, 1917. p. 309

21. Goldbeck, A. T., "Soil Pressure Cell Measures Accurately to Tenth of Pound." Public Roads, Vol. 3 (28), 1920.

22. Goldbeck, A.-T., "Measurement of Earth Pressures." Highway Research Board Proceedings, Vol. 18, Part II, 1938.

23. Goldbeck, A. T., "Studies of Subgrade Pressures Under Flexible Road Surfaces." Highway Research Board Proceedings, Vol. 19, 1939.

24. Goldbeck, A. T., "A Method of Design of Non-Rigid Pavements for Highways and Airport Runways." Highway Research Board Proceedings, Vol. 20, 1940.

25. Herner, Raymond C., and William M. Aldous, "The Load Transmission Test for Flexible Paving and Base Courses, Part I." Civil Aeronautics Administration, Technical Development Report No. 108, 1950.

26. Herner, Raymond C., "Progress Report on Load-Transmission Characteristics of Flexible Paving and Base Course." Highway Research Board Proceedings, Vol. 31, 1952. p. 125

27. Herner, Raymond C., "Effect of Base-Course Quality on Load Transmission Through Flexible Pavements." Highway Research Board Proceedings, Vol. 34, 1955. p. 224

28. Huntington, W. C., and E. J. Luetzelschwab, "New Type of Pressure Cell for Granular Material." Engineering News Record, Vol. 116, 1936. p. 20

29. Kögler, F., and A. Scheidig, "Druckverteilung Im Baugrunde." Die Bautechnik, No. 31, 1927.

30. Love, A. E. H., "The Stress Produced in a Semi-Infinite Solid by Pressure on Part of the Boundary." Philosophical Transactions of the Royal Society, Series A, Vol. 228, 1929.

31. Newmark, Nathan M., "Simplified Computation of Vertical Pressures in Elastic Foundations." Circular No. 24, Engineering Experiment Station, University of Illinois, 1935.

32. Palmer, L. A., "Stresses Under Circular Loaded Areas." Highway Research Board Proceedings, Vol. 19, 1939.

33. Palmer, L. A., and E. S. Barber, "Soil Displacement Under a Circular Loaded Area." Public Roads, Vol. 21, 1940.

34. Pickett, Gerald, M. E. Raville, W. C. James, and F. J. McCormick, "Deflections, Moments, and Reactive Pressures For Concrete Pavements." Kansas State College Experiment Station, Bulletin No. 65, 1951.

35. Price, Myron H., "Some Fundamentals of Flexible Pavement Design." Soil Mechanics and Foundation Engineering Conference, University of Kansas, 1954.

36. Rowe, Peter W., "A Soil Pressure Gauge for Laboratory Model Research." American Society of Civil Engineers, Separate No. 569, 1954.

37. Spangler, M. G., "Horizontal Pressure on Retaining Walls Due to Concentrated Surface Loads." Iowa State College Bulletin No. 140, Iowa State College, Ames, Iowa, 1938.

38. Spangler, M. G., "Wheel Load Stress Distribution Beneath Flexible Type Pavements." Proceedings, Conference on Soil Mechanics and Its Application, Purdue University, 1940. p. 312

39. Spangler, M. G., "Wheel Load Distribution Through Flexible Type Pavements." Highway Research Board Proceedings, Vol. 21, 1941. p. 110

40. Spangler, M. C., and H. O. Ustrud, "Wheel Load Distribution Through Flexible Type Pavements." Highway Research Board Proceedings, Vol. 20, 1940.

41. Teller, L. W., and J. A. Buchanan, "Determination of Variation in Unit Pressure Over the Contact Area of Tires." Public Roads, Vol. 18, No. 10, 1937.

42. Timoshenko, S., "Theory of Elasticity." McGraw-Hill, New York, 1934.

43. Timoshenko, S., and J. N. Goodier, "Theory of Elasticity." McGraw-Hill, New York, 1951.

44. Tschebotarioff, Gregory P., "Soil Mechanics, Foundations, and Earth Structures." McGraw-Hill, New York, 1951.

General References

45. Baker, R. F., and W. B. Drake, "Investigation of Field and Laboratory Methods for Evaluating Subgrade Support in the Design of Highway Flexible Pavements." Highway Research Board Proceedings, Vol. 28, 1948, p. 60.

46. Bleck, A. T., "Pavements and Influences Affecting or Determining Their Performance." Highway Research Board Bulletin No. 20, 1949, p. 21.

47. Evans, W. H., "Dynamometers for Measuring Earth Pressures." London, England, Engineering, Vol. 149, No. 3876, April, 1940.

48. Feld, J., "Measured Retaining Wall Pressure From Sand and Surcharge." Engineering News Record, Vol. 88, 1922, p. 106.

49. Feld, J., "Lateral Earth Pressure. The Accurate Experimental Determination of the Lateral Earth Pressure, Together with a Resume of Previous Experiments." Transactions, American Society of Civil Engineers, Vol. 86, 1923, p. 1448.

50. Hicks, L. D., "Flexible Pavement Design as Revised for Heavy Traffic." Highway Research Board, Research Report No. 16B, 1954, p. 29.

51. Hveem, F. N., and R. M. Carmany, "The Factors Underlying the Rational Design of Pavements." Highway Research Board Proceedings, Vol. 28, 1948, p. 101.

52. Livingston, R. E., "Design of Flexible Bases." Highway Research Board Proceedings, Vol. 27, 1947, p. 92.

53. Lowe, John, "An Apparatus for Measuring Slab Action in Flexible Type Pavements." Highway Research Board Proceedings, Vol. 23, 1943, p. 117.

54. Lowe, John, "An Apparatus for Determining Pressure Distributions." Society of Experimental Stress Analysis, Vol. 2 (1), 1944, p. 41.

55. McLeod, Norman W., "Some Basic Problems in Flexible Pavement Design." Highway Research Board Proceedings Vol. 32, 1953, p. 90.

56. McLeod, Norman W., "Flexible Pavement Design." Highway Research Board Bulletin No. 90, 1953.

57. McNary, J. V., "Earth Pressure Against Abutment Walls Measured With Soil Pressure Cells." Public Roads, Vol. 6, 1925, p. 102.

58. Morrison, I. F., and W. E. Cornish, "Measurements of Earth Pressure." Canadian Journal of Research, Vol. 17, Section A, 1939.

59. Nevitt, H. G., "A Mathematical Analysis of Some Phases of the Flexible Surface Design Problem." Highway Research Board Proceedings, Vol. 23, 1943.

60. Perry, C. C., and H. R. Lissner, "The Strain Gage Primer." McGraw-Hill, New York, 1954.

61. Seaquist, W. H., "Accuracy of Goldbeck Cell in Laboratory Tests." Engineering News Record, Vol. 112, 1934, p. 730.

APPENDIX A

SAMPLE COMPUTATIONS OF CELL DIAPHRAM DESIGN

Assume $a = r = 0.5"$ $h = t = 0.02"$

Maximum Allowable Pressure q

Timoshenko $-\sigma = \frac{3q\,a^2}{4h^2}$

$$q = \frac{\sigma 4h^2}{3a^2}$$

$$= \frac{30{,}000 \times 4 \times .0004}{3 \times .25}$$

$$q = 64 \text{ psi}$$

Deflection at the Center

Timoshenko $-w = \frac{q}{45\,D}(a^4)$

$$w = \frac{64}{64 \times 21.3} \times .0625$$

$$w = .003"$$

$D = \frac{E\,t^3}{12(1 - \sigma^2)}$

E = Modulus of Elasticity

t = diaphram thickness

σ = Poisson's Ratio

$$D = \frac{30{,}000{,}000 \times .0004 \times .02}{12(.9375)}$$

$$D = 21.3$$

Stress at the Center

$$\sigma_c = \frac{3(1 + u)q\,a^2}{8\,h^2}$$

$$= \frac{3 \times 1.25 \times 64 \times .25}{8 \times .0004}$$

$$= 18{,}750 \text{ psi}$$

Assumed values are valid.

APPENDIX B

TABLE 1

Laboratory Pressure Cell Measurements

Series 2
Soil Only

Cell No.	0	4	5	7	8
Cover	2"	2"	2"	2"	2"
% Applied Stress	-3.6	0	0	11.2	70.3
Cover	4"	4"	4"	4"	4"
% Applied Stress	0	0	7.21	17.3	41.8
Cover	6"	6"	6"	6"	6"
% Applied Stress	2.70	0	6.49	9.73	19.81
Cover	8"	8"	8"	8"	8"
% Applied Stress	4.0	2.60	5.51	5.41	9.0
Cover	10"	10"	10"	10"	10"
% Applied Stress	4.58	2.60	4.9	6.49	6.59
Cover	12"	12"	12"	12"	12"
% Applied Stress	3.7	1.6	4.7	5.0	3.8

TABLE 2

Laboratory Pressure Cell Measurements

Series 2
Crushed Rock Base

Cell No.	0	4	5	7	8
Cover		4" soil plus 4" aggregate			
% Applied Stress	3.06	1.4	6.55	9.01	21.08
Cover		6" soil plus 4" aggregate			
% Applied Stress	4.86	.72	5.88	7.65	9.95
Cover		8" soil plus 4" aggregate			
% Applied Stress	3.60	2.27	3.97	4.5	4.76

TABLE 3

Laboratory Pressure Cell Measurements

Series 2
Glacial Gravel Cover

Cell No.	0	4	5	7	8
Cover		4" soil plus 4" gravel			
% Applied Stress	3.60	0	8.18	9.0	22.0
Cover		6" soil plus 4" gravel			
% Applied Stress	4.86	0.76	5.55	6.49	9.9
Cover		8" soil plus 4" gravel			
% Applied Stress	5.16	2.92	7.5	5.41	6.16

APPENDIX C

TABLE 4

Laboratory Pressure Cell Measurements

Series 3
Soil Only

Cell No.	8	4	12	11	2	10	7
Cover			4" soil only				
% Applied Stress	7.43	34.2	0.59	0.73	19.0	0.7	5.5
Cover			6" soil only				
% Applied Stress	5.4	14.3	0.75	0.56	9.25	1.1	4.7
Cover			8" soil only				
% Applied Stress	4.2	1.4	0.99	0.56	4.86	1.0	3.74
Cover			10" soil only				
% Applied Stress	3.1	3.6	0.75	0.72	3.2	1.3	2.64
Cover			12" soil only				
% Applied Stress	1.53	1.75	0.78	.914	2.44	0.46	2.07

Cells 9 and 13 failed to function.

TABLE 5

Field Pressure Cell Data

Full Soil Cover No Limestone

Series I
July 28, 1958

Plate Size 18"
Applied Stress 22.9

Cell No.	8	2	7	17	14	5	4	13	11
Depth	16	16	16	16	16	16	16	16	16
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.	1.0	0	5.9	2.5	0.5	2.8	10.9	4.68	1.7
% A. S.	4.4	0	25.8	11.0	2.2	12.0	40.8	22.0	7.5
Angle			45	90		90			45

Plate Size 12"
Applied Stress 33.0

Cell No.	8	2	7	17	14	5	4	13	11
Depth	16	16	16	16	16	16	16	16	16
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.	0	0	3.8	1.25	.2	1.7	8.7	1.8	1.4
% A. S.	0	0	11.5	3.8	0.7	5.1	26.2	5.4	4.2
Angle			45	90		90			45

Plate Size 7 3/16"
Applied Stress 30.1

Cell No.	8	2	7	17	14	5	4	13	11
Depth	16	16	16	16	16	16	16	16	16
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.	0	0	1.1	.5	0	.5	3.1	.42	.28
% A. S.			3.8	1.75		1.8	10.3	1.4	.9
Angle			45	90		90			45

TABLE 5
(cont'd)

Field Pressure Cell Data

Full Soil Cover No Limestone

Series I
July 28, 1958

Plate Size 18"
Applied Stress 22.9

Cell No.	10	16	15	12	6	22	18	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0.6	2.6	4.7	2.0	0	0	0.7	1.0	1.92
% A. S.	2.6	11.2	20.8	8.7	0	0	3.0	4.4	8.4
Angle									

Plate Size 12"
Applied Stress 33.0

Cell No.	10	16	15	12	6	22	18	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	.62	1.8	3.3	.8	0	0	0	.75	1.15
% A. S.	1.88	5.4	10.3	2.6	0	0	0	2.3	3.5
Angle									

Plate Size 7 3/16"
Applied Stress 30.1

Cell No.	10	16	15	12	6	22	18	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0	.56	1.0	.29	0	0	0	0	0
% A. S.		1.85	3.3	.95					
Angle									

TABLE 6

Field Pressure Cell Data

(-)4" Soil No Limestone

Series I
July 29, 1958

Plate Size 18"
Applied Stress 14.7 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	12	12	12	12	12	12	12	12	12
Dist. ℄	1.5'	2.5'	1'	2'	2'	1'	C	1'	2'
Meas. Str.			3.5	1.05	.33	1.1	9.4	4.1	1.1
% A. S.	0	0	24.0	7.0	2.2	7.6	64.0	28.0	7.5
Angle			45	90		90			45

Plate Size 12"
Applied Stress 23.9 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	12	12	12	12	12	12	12	12	12
Dist. ℄	1.5'	2.5'	1'	2'	2'	1'	C	1'	2'
Meas. Str.			3.0	.35		1.34	9.7	1.88	.86
% A. S.	0		12.5	1.45	0	5.6	41.0	7.9	3.6
Angle			45	90		90			45

Plate Size 7 3/16"
Applied Stress 41.8 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	12	12	12	12	12	12	12	12	12
Dist. ℄	1.5'	2.5'	1'	2'	2'	1'	C	1'	2'
Meas. Str.			1.8			1.05	6.2		.6
% A. S.	0	0	4.3	0	0	2.5	14.8	0	1.43
Angle			45	90		90			45

TABLE 6
(cont'd)

Field Pressure Cell Data

(-)4" Soil No Limestone

Series I
July 29, 1958

Plate Size 18"
Applied Stress 14.7 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	20	20	20	20	20	32	32	32	32
Dist. ℄	2'	1'	C	18"	30"	3'	2'	1'	C
Meas. Str.	.47	1.73	3.75	.7			.7	.6	1.1
% A. S.	3.2	11.7	25.5	4.8	0	0	4.8	4.1	7.5
Angle									

Plate Size 12"
Applied Stress 23.9 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	20	20	20	20	20	32	32	32	32
Dist. ℄	2'	1'	C	18"	30"	3'	2'	1'	C
Meas. Str.	0	1.0	2.5	.3			.4	.6	.8
% A. S.	0	4.2	10.5	1.25	0	0	1.65	2.5	3.5
Angle									

Plate Size 7 3/16"
Applied Stress 41.8 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	20	20	20	20	20	32	32	32	32
Dist. ℄	2'	1'	C	18"	30"	3'	2'	1'	C
Meas. Str.			1.25						.5
% A. S.	0	0	3.0	0	0	0	0	0	1.3
Angle									

TABLE 7

Field Pressure Cell Data

(-)8" Soil No Limestone

Series I
Aug. 1, 1958

Plate Size 18"
Applied Stress 14.7 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	8	8	8	8	8	8	8	8	8
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	C	1.0	2.0
Meas. Str.			4.82	1.07	0.3	1.72	12.8	3.0	.5
% A. S.			32.8	7.2	2.0	11.6	87.0	20.4	3.9
Angle			45	90		90			45

Plate Size 12"
Applied Stress 23.9

Cell No.	8	2	7	17	14	5	4	13	11
Depth	8	8	8	8	8	8	8	8	8
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	C	1.0	2.0
Meas. Str.			3.4		0	1.67	15.35	1.0	0.6
% A. S.			14.3		0	7.0	64.0	4.2	2.8
Angle			45	90		90			45

Plate Size 7 3/16"
Applied Stress 41.8 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	8	8	8	8	8	8	8	8	8
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	C	1.0	2.0
Meas. Str.			1.88			1.11	14.8	1.67	.42
% A. S.			4.5			2.6	34.0	4.0	1.02
Angle			45	90		90			45

TABLE 7
(cont'd)

Field Pressure Cell Data

(-)8" Soil No Limestone

Series I
Aug. 1, 1958

Plate Size 18"
Applied Stress 14.7 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	16	16	16	16	16	28	28	28	28
Dist. ^{C}L	2.0	1.0	C	1.5	2.5	3.0	2.0	1.0	C
Meas. Str.	.344	2.41	5.6	0.51		0.73		.6	1.38
% A. S.	2.36	16.3	38.0	3.5		5.0		4.1	9.4
Angle									

Plate Size 12"
Applied Stress 23.9

Cell No.	10	16	15	12	6	22	18	19	23
Depth	16	16	16	16	16	28	28	28	28
Dist. ^{C}L	2.0	1.0	C	1.5	2.5	3.0	2.0	1.0	C
Meas. Str.	0	1.30	4.9	.08	0	.13	0	.51	1.11
% A. S.		5.4	20.5	.36		0.6		2.15	4.6
Angle									

Plate Size 7 3/16"
Applied Stress 41.8 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	16	16	16	16	16	28	28	28	28
Dist. ^{C}L	2.0	1.0	C	1.5	2.5	3.0	2.0	1.0	C
Meas. Str.	0	.704	3.05	0	0	0	.19	0	.69
% A. S.		1.7	7.2				.43		1.65
Angle									

TABLE 8

Field Pressure Cell Data

(-)12" Soil No Limestone

Series I
Aug. 6, 1958

Plate Size 18"
Applied Stress 18.7

Cell No.	8	2	7	17	14	5	4	13	11
Depth - in.	4	4	4	4	4	4	4	4	4
Dist. ℄	1.5'	2.5'	1'	2'	2'	1'	C	1'	2'
Meas. Stress	.5	.87	5.4	.714	0.1	1.65	18.6	1.66	.6
% A. S.	2.7		29.0	3.8	0.5	8.5	99.5	8.5	3.4
Angle			45	90		90			45

Plate Size 12"
Applied Stress 23.9 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth - in.	4	4	4	4	4	4	4	4	4
Dist. ℄	1.5'	2.5'	1'	2'	2'	1'	C	1'	2'
Meas. Stress	0	0	2.06	.53		1.22	20.7		.43
% A. S.			7.75	2.2		5.1	86.5		1.8
Angle			45	90		90			45

Plate Size 7 3/16"
Applied Stress 41.8 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth - in.	4	4	4	4	4	4	4	4	4
Dist. ℄	1.5'	2.5'	1'	2'	2'	1'	C	1'	2'
Meas. Stress			1.12	0.286		.445	27.3	.835	.343
% A. S.			2.7	0.7		1.1	65.6	2.0	.697
Angle			45	90		90			45

TABLE 8
(cont'd)

Field Pressure Cell Data

(-)12" Soil No Limestone

Series I
Aug. 6, 1958

Plate Size 18"
Applied Stress 18.7

Cell No.	10	16	15	12	6	22	18	19	23
Depth - in.	12	12	12	12	12	24	24	24	24
Dist. ℄	2'	1'	C	18"	30"	3'	2'	1'	C
Meas. Stress	0	2.84	10.5	1.06	1.0	.266	.79	1.6	3.41
% A. S.		15.1	53.8	5.4	5.1	1.45	4.2	8.2	18.1
Angle									

Plate Size 12"
Applied Stress 23.9 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth - in.	12	12	12	12	12	24	24	24	24
Dist. ℄	2'	1'	C	18"	30"	8'	2'	1'	C
Meas. Stress		1.33	8.55	.28			.356	.76	1.92
% A. S.		5.6	36.0	1.2			1.5	3.2	8.05
Angle									

Plate Size 7 3/16"
Applied Stress 41.8 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth - in.	12	12	12	12	12	24	24	24	24
Dist. ℄	2'	1'	C	18"	30"	3'	2'	1'	C
Meas. Stress	.156	.74	6.3	.1			.356	.485	1.0
% A. S.	.37	1.75	15.0	.25	0	0	.85	1.15	2.5
Angle									

TABLE 9

Field Pressure Cell Data

Full Soil Cover No Limestone

Series II
Aug. 15, 1958

Plate Size 18"
Applied Stress 18.7 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth - in.	16	16	16	16	16	16	16	16	16
Dist. ℄	1.0	C	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Stress	1.72	7.47	3.46		0.31	6.23	1.30	5.73	1.0
% A. S.	9.2	40.0	18.5		1.7	33.5	7.0	31.0	5.3
Angle									

Plate Size 12"
Applied Stress 33.0 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth - in.	16	16	16	16	16	16	16	16	16
Dist. ℄	1.0	C	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Stress	1.44	8.0	2.38		0.28	6.23	0.76	4.94	0.66
% A. S.	4.35	24.2	7.2		.86	18.8	2.32	14.9	2.0

Plate Size 7 3/16"
Applied Stress 41.8 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth - in.	16	16	16	16	16	16	16	16	16
Dist. ℄	1.0	C	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Stress	0.92	5.33	1.15			3.70	2.66	2.94	
% A. S.	1.7	9.8	2.13			6.8	4.9	5.4	

TABLE 9
(cont'd)

Field Pressure Cell Data

Full Soil Cover No Limestone

Series II
Aug. 15, 1958

Plate Size 18"
Applied Stress 18.7 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth - in.	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	C	1.5	2.5	3.0	2.0	1.0	C
Meas. Stress	0.34	1.89	3.4	1.11			0.60	0.66	1.34
% A. S.	1.85	10.1	18.2	5.9			3.25	.36	7.2

Plate Size 12"
Applied Stress 33.0 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth - in.	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	C	1.5	2.5	3.0	2.0	1.0	C
Meas. Stress	0.37	1.44	2.9	0.62			0.35	0.45	1.03
% A. S.	1.13	4.36	8.8	1.9			1.08	1.37	3.13

Plate Size 7 3/16"
Applied Stress 41.8 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth - in.	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	C	1.5	2.5	3.0	2.0	1.0	C
Meas. Stress	0.63	0.74	1.65	0.35	0.33	0.10	0.21	0.34	0.42
% A. S.	.11	1.37	3.03	.66	.61	.18	0.4	.64	.78

TABLE 10

Field Pressure Cell Data

(-)4" Soil No Limestone

Series II
Aug. 18, 1958

Plate Size 18"
Applied Stress 18.7

Cell No.	28	30	13	26	11	8	14	5	17
Depth - in.	12	12	12	12	12	12	12	12	12
Dist. ℄	1.0	C	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Stress	2.32	11.3	3.08		0.372	8.09	0.80	8.0	
% A. S.	12.3	60.0	16.4		2.0	43.0	4.2	42.6	

Plate Size 12"
Applied Stress 33.0

Cell No.	28	30	13	26	11	8	14	5	17
Depth - in.	12	12	12	12	12	12	12	12	12
Dist. ℄	1.0	C	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Stress	1.64	13.0	2.08		0.26	8.0	0.33	7.5	
% A. S.	5.0	39.5	6.4		.78	24.2	1.0	22.8	

Plate Size 7 3/16"
Applied Stress 41.8

Cell No.	28	30	13	26	11	8	14	5	17
Depth - in.	12	12	12	12	12	12	12	12	12
Dist. ℄	1.0	C	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Stress	0.40	6.7	0.615		0	4.31	0	3.28	
% A. S.	.95	16.0	1.47			10.3		7.8	

TABLE 10
(cont'd)

Field Pressure Cell Data

(-)4" Soil No Limestone

Series II
Aug. 18, 1958

Plate Size 18"
Applied Stress 18.7

Cell No.	10	16	15	12	6	22	18	19	23
Depth - in.	20	20	20	20	20	32	32	32	32
Dist.℄	2.0	1.0	C	1.5	2.5	3.0	2.0	1.0	C
Meas. Stress		2.41	4.67	1.14	0.66		0.53	0.88	1.77
% A. S.		12.8	24.8	6.1	3.5		2.85	4.7	9.5

Plate Size 12"
Applied Stress 33.0

Cell No.	10	16	15	12	6	22	18	19	23
Depth - in.	20	20	20	20	20	32	32	32	32
Dist.℄	2.0	1.0	C	1.5	2.5	3.0	2.0	1.0	C
Meas. Stress	0.5	1.925	4.43	0.77			0.465	0.667	1.305
% A. S.	1.5	5.85	13.4	2.34			1.41	2.0	4.0

Plate Size 7 3/16"
Applied Stress 41.8

Cell No.	10	16	15	12	6	22	18	19	23
Depth - in.	20	20	20	20	20	32	32	32	32
Dist.℄	2.0	1.0	C	1.5	2.5	3.0	2.0	1.0	C
Meas. Stress	0	0.74	1.55		0	0	0.286	0.6	0.5
% A. S.		1.77	3.7				.68	1.43	1.20

TABLE 11

Field Pressure Cell Data

(-)4" Soil (+)4" Limestone

Series I
July 30, 1958

Plate Size 18"
Applied Stress 31.5 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	16	16	16	16	16	16	16	16	16
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.	1.0	2.1	8.85	2.85	.66	4.0	13.5	8.5	3.0
% A. S.	3.0	6.7	28.0	9.0	2.1	12.7	43.0	27.0	9.5
Angle			45	90		90			45

Plate Size 12"
Applied Stress 33.0 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	16	16	16	16	16	16	16	16	16
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.			3.8	1.3	.	2.2	9.0	2.1	1.1
% A. S.			11.5	4.0		6.7	27.3	6.3	3.4
Angle			45	90		90			45

Plate Size 7 3/16
Applied Stress 41.8

Cell No.	8	2	7	17	14	5	4	13	11
Depth	16	16	16	16	16	16	16	16	16
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.			1.5	0.7	0	1.1	5.1	2.3	0.4
% A. S.			3.5	1.7	2.6	12.2	5.6	1.0	0
Angle			45	90		90			45

TABLE 11
(cont'd)

Field Pressure Cell Data

(-)4" Soil (≠)4" Limestone

Series I
July 30, 1958

Plate Size 18"
Applied Stress 31.5 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist.℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	.78	4.1	6.5	3.1			1.42	1.82	3.25
% A. S.	2.5	12.9	20.7	9.7			4.5	5.8	10.3
Angle									

Plate Size 12"
Applied Stress 33.0 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist.℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	.15	1.9	3.3	.9		.19	.6	.6	.96
% A. S.	0.5	5.6	9.8	2.6		0.6	1.8	1.8	2.8

Plate Size 7 3/16"
Applied Stress 41.8

Cell No.	10	16	15	12	6	22	18	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist.℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0	1.2	2.0	0.4	0	0	0	0	.4
% A. S.	0	2.9	4.8	1.0	0	0	0	0	1.0

TABLE 12

Field Pressure Cell Data

(-)4" Soil (+)4" Limestone

Series I
(rerun)

Plate Size 18"
Applied Stress 22.9 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	16	16	16	16	16	16	16	16	16
Dist.℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	0
Meas. Str.	1.8	.75	6.5	3.2		2.5	11.2	6.7	2.1
% A. S.	6.0	3.3	28.0	14.0		10.8	48.0	28.8	9.3
Angle			45	90		90			45

Plate Size 12"
Applied Stress 33.0 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	16	16	16	16	16	16	16	16	16
Dist.℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.	0	0	2.5	1.1	0	2.0	9.6	3.3	1.3
% A. S.	0	0	7.7	3.3	0	6.1	29.0	10.1	3.9
Angle			45	90		90			45

TABLE 12
(cont'd)

Field Pressure Cell Data

(-)4" Soil (+)4" Limestone

Series I
(rerun)

Plate Size 18"
Applied Stress 22.9 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0.8	3.3	5.9	1.2		0.3	0.7	1.0	1.7
% A. S.	3.3	14.5	25.5	5.3		1.4	3.1	4.3	7.2
Angle									

Plate Size 12"
Applied Stress 33.0 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0.3	1.8	4.0	0.9		.33	0.3	0.6	1.1
% A. S.	0.9	5.4	12.1	2.6		1.0	0.9	1.8	3.2
Angle									

TABLE 13

Field Pressure Cell Data

(-)8" Soil (+)4" Limestone

Series I

Plate Size 18"
Applied Stress 22.9 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	12	12	12	12	12	12	12	12	12
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.	.36	1.12	8.6	1.0		2.9	13.5	5.4	1.6
% A. S.	1.6	4.9	36.6	4.4		12.7	58.8	23.6	7.1
Angle			45	90		90			45

Plate Size 12"
Applied Stress 33.0 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	12	12	12	12	12	12	12	12	12
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.			6.1	1.35	0	1.6	12.8	2.3	1.0
% A. S.			18.5	4.1	0	4.7	38.8	7.1	3.0
Angle			45	90		90			45

Plate Size 7 3/16"
Applied Stress 54.2 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	12	12	12	12	12	12	12	12	12
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.			3.5	0.7	0	1.6	10.7	1.3	0.7
% A. S.			6.4	1.3	0	3.0	19.8	2.3	1.4
Angle			45	90		90			45

TABLE 13
(cont'd)

Field Pressure Cell Data

(-)8" Soil (⌿)4" Limestone

Series I

Plate Size 18"
Applied Stress 22.9 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	20	20	20	20	20	32	32	32	32
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	.65	3.8	7.0	2.0	.3	.19	0.6	1.2	2.2
% A. S.	2.9	16.5	30.6	8.6	1.4	0.8	2.6	5.2	9.9
Angle									

Plate Size 12"
Applied Stress 33.0 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	20	20	20	20	20	32	32	32	32
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0.4	2.3	5.0	1.1	0	0.1	0.36	0.7	1.4
% A. S.	1.2	7.0	15.2	3.3	0	0.3	1.1	2.1	4.3
Angle									

Plate Size 7 3/16"
Applied Stress 54.2 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	20	20	20	20	20	32	32	32	32
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	.22	1.3	3.3	.31	0	0	.21	.36	.85
% A. S.	0.4	2.5	6.0	0.6	0	0	0.4	0.7	1.6

TABLE 14

Field Pressure Cell Data

(-)12" Soil (+)4" Limestone

Series I

Plate Size 18"
Applied Stress 18.7 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	8	8	8	8	8	8	8	8	8
Dist.℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.	0.36		7.3	1.3	0.3	2.3	12.9	4.5	0.86
% A. S.	1.9		39.0	6.7	1.8	12.2	69.0	24.2	4.6
Angle			45	90		90			45

Plate Size 12"
Applied Stress 33.0 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	8	8	8	8	8	8	8	8	8
Dist.℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.			5.8	1.1	0	1.9	15.2	1.7	.66
% A. S.			17.4	3.4		5.9	46.2	5.1	2.0
Angle			45	90		90			45

Plate Size 7 3/16"
Applied Stress 65.6 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	8	8	8	8	8	8	8	8	8
Dist.℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.			3.4	0.9		1.6	18.1	.83	0.6
% A. S.			5.2	1.4		2.7	27.4	1.3	0.9
Angle			45	90		90			45

TABLE 14
(cont'd)

Field Pressure Cell Data

(-)12" Soil (≠)4" Limestone

Series I

Plate Size 18"
Applied Stress 18.7 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	16	16	16	16	16	28	28	28	28
Dist.℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0.38	3.2	7.8	1.4		0.3	0.43	0.9	2.3
% A. S.	2.0	17.0	41.5	7.5		1.8	2.3	4.7	12.3
Angle									

Plate Size 12"
Applied Stress 33.0 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	16	16	16	16	16	28	28	28	28
Dist.℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0	2.5	7.7	0.8	0	0	0.36	0.85	2.0
% A. S.	0	7.6	23.3	2.5	0	0	1.1	2.7	6.2

Plate Size 7 3/16"
Applied Stress 65.6 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	16	16	16	16	16	28	28	28	28
Dist.℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0	1.5	6.3	.43			0	0.52	1.8
% A. S.	0	2.3	10.3	0.7			0	0.8	2.7
Angle									

TABLE 15

Field Pressure Cell Data

(-)4" Soil (+)4" Limestone

Series II
Aug. 19, 1958

Plate Size 18"
Applied Stress 22.9 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth	16	16	16	16	16	16	16	16	16
Dist.℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.	3.9	10.4	3.6		0.8	7.1	1.47	7.5	
% A. S.	17.0	45.3	15.5		3.5	30.8	6.4	32.4	

Plate Size 12"
Applied Stress 33.0 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth	16	16	16	16	16	16	16	16	16
Dist.℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.	1.36	8.5	1.9		0.5	5.8	0.93	5.5	
% A. S.	4.1	25.6	5.8		1.4	17.6	2.8	16.7	

Plate Size 7 3/16"
Applied Stress 65.6 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth	16	16	16	16	16	16	16	16	16
Dist.℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.	1.26	7.6	1.46		0.34	4.6	0.37	4.55	
% A. S.	1.9	11.5	2.2		0.5	7.0	0.6	6.9	

TABLE 15
(cont'd)

Field Pressure Cell Data

(-)4" Soil (+)4" Limestone

Series II
Aug. 19, 1958

Plate Size 18"
Applied Stress 22.9 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	.38	2.5	4.3	1.4		0.2	0.82	0.9	1.77
% A. S.	1.6	10.8	18.5	6.0		0.9	3.6	4.0	7.7

Plate Size 12"
Applied Stress 33.0 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.		1.3	3.0	.62		0.07	0.42	.46	1.04
% A. S.		3.8	9.1	1.9		0.2	1.3	1.4	3.1

Plate Size 7 3/16"
Applied Stress 65.6 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.		.93	2.05	0.4			0.32	0.30	0.8
% A. S.		1.4	3.1	0.6			0.5	0.5	1.2

TABLE 16

Field Pressure Cell Data

(-)8" Soil (+)4" Limestone

Series II
Aug. 21, 1958

Plate Size 18"
Applied Stress 22.9 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth	12	12	12	12	12	12	12	12	12
Dist. ℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.	4.7	11.3	5.7		.34	9.3	1.3	8.5	
% A. S.	20.3	49.5	24.8		1.5	40.5	5.5	36.8	

Plate Size 12"
Applied Stress 42.0 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth	12	12	12	12	12	12	12	12	12
Dist. ℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.	2.4	15.7	3.8		.26	10.4	.54	9.3	
% A. S.	5.7	37.1	8.9		0.6	24.7	1.3	22.2	

Plate Size 7 3/16
Applied Stress 54.2 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth	12	12	12	12	12	12	12	12	12
Dist. ℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.	.73	10.4	0.78		0.21	6.0		4.8	
% A. S.	1.4	19.0	1.4		0.4	11.0		8.9	

TABLE 16
(cont'd)

Field Pressure Cell Data

(-)8" Soil (+)4" Limestone

Series II
Aug. 21, 1958

Plate Size 18"
Applied Stress 22.9 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	20	20	20	20	20	32	32	32	32
Dist.℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	.7		5.2	1.6		.27	.64	1.1	2.2
% A. S.	3.1		22.5	6.9		1.2	2.8	4.8	9.4

Plate Size 12"
Applied Stress 42.0 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	20	20	20	20	20	32	32	32	32
Dist.℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	.25		5.6	1.1			.54	1.1	2.0
% A. S.	0.6		13.3	2.7			1.3	2.7	4.7

Plate Size 7 3/16
Applied Stress 54.2 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	20	20	20	20	20	32	32	32	32
Dist.℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.			2.5	0.51			.14	.36	.77
% A. S.			4.6	0.6			0.3	0.7	1.4

TABLE 17

Field Pressure Cell Data

(-)12" Soil (+)4" Limestone

Series II

Plate Size 18"
Applied Stress 22.9 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth	8	8	8	8	8	8	8	8	8
Dist. ℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.		16.7	5.8			12.9		12.1	
% A. S.		72.8	25.2			56.1		52.7	

Plate Size 12"
Applied Stress 33.0 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth	8	8	8	8	8	8	8	8	8
Dist. ℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.	1.9	17.8	1.5		0.3	11.0	0.33	9.55	
% A. S.	5.7	54.3	4.5		0.9	33.3	1.0	28.8	

Plate Size 7 3/16
Applied Stress 54.2

Cell No.	28	30	13	26	11	8	14	5	17
Depth	8	8	8	8	8	8	8	8	8
Dist. ℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.	0.9	17.7			.086	6.7	0.13	6.1	
% A. S.	1.7	32.8			0.2	12.3	0.25	11.3	

TABLE 17
(cont'd)

Field Pressure Cell Data

(-)12" Soil (+)4" Limestone

Series II

Plate Size 18"
Applied Stress 22.9 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	16	16	16	16	16	28	28	28	28
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	.52		8.3	1.6		0.3	0.7		2.6
% A. S.	2.2		36.0	7.0		1.2	3.1		10.2

Plate Size 12"
Applied Stress 33.0 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	16	16	16	16	16	28	28	28	28
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0.14		6.9	0.69			.36		1.6
% A. S.	0.4		20.8	2.1			1.1		4.9

Plate Size 7 3/16
Applied Stress 54.2 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	16	16	16	16	16	28	28	28	28
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	.047		4.6			0.13	.29		0.94
% A. S.	.1		8.5			0.25	0.5		1.7

TABLE 18

Field Pressure Cell Data

(-)8" Soil (≠)8" Limestone

Series I

Plate Size 18"
Applied Stress 31.5 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	16	16	16	16	16	16	16	16	16
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.	0.9	1.63	8.6	3.0	.54	4.4	11.3	6.0	2.72
% A. S.	2.9	5.2	27.3	9.5	1.7	14.1	35.7	19.0	8.6
Angle			45	90		90			45

Plate Size 12"
Applied Stress 51.4 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	16	16	16	16	16	16	16	16	16
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.	.46	.75	6.95	2.3		2.8	12.2	4.6	2.1
% A. S.	0.9	1.4	13.5	4.4		5.5	23.8	9.0	4.2
Angle			45	90		90			45

Plate Size 7 3/16"
Applied Stress 54.2 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	16	16	16	16	16	16	16	16	16
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.	0.27	0	3.18	.89	0	1.0	5.63	1.2	0.63
% A. S.	0.5	0	5.8	1.65	0	1.8	10.4	2.1	1.2
Angle			45	90		90			45

TABLE 18
(cont'd)

Field Pressure Cell Data

(-)8" Soil (+)8" Limestone

Series I

Plate Size 18"
Applied Stress 31.5 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0.94	4.2	6.9	2.5	.67		.82	1.45	2.8
% A. S.	2.98	13.2	21.9	8.0	2.1		2.6	4.6	8.8
Angle									

Plate Size 12"
Applied Stress 51.4 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	.38	2.9	6.0	1.8			.68	1.3	2.4
% A. S.	0.7	5.6	11.5	3.5			1.3	2.5	4.6

Plate Size 7 3/16"
Applied Stress 54.2 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.		.90	2.0	.52			.32	.49	.88
% A. S.		1.65	3.7	0.95			0.6	0.9	1.6

TABLE 19

Field Pressure Cell Data

(-)12" Soil (⌿)8" Limestone

Series I

Plate Size 18"
Applied Stress 22.9 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	12	12	12	12	12	12	12	12	12
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.		1.13	6.8	1.54		2.8	8.9	6.8	1.5
% A. S.		4.9	29.5	6.7		12.0	38.8	29.8	6.7
Angle			45	90		90			45

Plate Size 12"
Applied Stress 42.0psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	12	12	12	12	12	12	12	12	12
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.			6.95	1.4		2.61	10.6	5.3	1.1
% A. S.			16.5	3.2		6.2		12.5	2.7
Angle			45	90		90			45

Plate Size 7 3/16
Applied Stress 92.0 psi

Cell No.	8	2	7	17	14	5	4	13	11
Depth	12	12	12	12	12	12	12	12	12
Dist. ℄	1.5	2.5	1.0	2.0	2.0	1.0	0	1.0	2.0
Meas. Str.			5.0	1.1		2.0	10.6	2.7	0.86
% A. S.			5.5	1.2		2.2	11.5	3.0	0.9
Angle			45	90		90			45

TABLE 19
(cont'd)

Field Pressure Cell Data

(-)12" Soil (+)8" Limestone

Series I

Plate Size 18"
Applied Stress 22.9 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	20	20	20	20	20	32	32	32	32
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0.7	3.3	6.5	1.3			0.64	1.2	2.4
% A. S.	3.0	14.3	28.5	5.7			2.8	5.3	10.4

Plate Size 12"
Applied Stress 42.0 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	20	20	20	20	20	32	32	32	32
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	.437	2.9	6.7	1.3	0.67	0.17	0.36	0.9	2.1
% A. S.	1.0	6.9	15.7	3.0	1.6	0.4	0.9	2.1	5.1

Plate Size 7 3/16"
Applied Stress 92.0 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	20	20	20	20	20	32	32	32	32
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0.25	2.0	5.7	0.9	0	0	0.36	0.85	1.85
% A. S.	0.27	2.2	6.3	1.0	0	0	0.4	0.9	2.0

TABLE 20

Field Pressure Cell Data

(-)8" Soil (+)8" Limestone

Series II

Plate Size 18"
Applied Stress 22.9 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth	16	16	16	16	16	16	16	16	16
Dist. ℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.	3.45	7.6	5.15		7.4	6.76	1.57	6.1	
% A. S.	14.6	32.3	21.8		3.12	28.6	6.65	25.6	

Plate Size 12"
Applied Stress 42.0 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth	16	16	16	16	16	16	16	16	16
Dist. ℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.	3.2	0.6	3.5		.32	7.0	.93	6.4	
% A. S.	7.6	22.8	8.3		0.76	16.5	2.2	15.3	

Plate Size 7 3/16"
Applied Stress 54.2 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth	16	16	16	16	16	16	16	16	16
Dist. ℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.	1.5	5.5	1.6		0	3.5	.23	3.4	
% A. S.	2.8	10.1	3.0		0	6.4	0.4	6.3	

TABLE 20
(cont'd)

Field Pressure Cell Data

(-)8" Soil (+)8" Limestone

Series II

Plate Size 18"
Applied Stress 22.9 psi

Cell No.	10	16	15	12	6	22	13	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	.312		3.64	1.42	.66		0.5	1.1	1.57
% A. S.	1.34		15.4	6.0	2.8		2.1	4.7	6.7

Plate Size 12"
Applied Stress 42.0 psi

Cell No.	10	16	15	12	6	22	13	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	.66		3.8	1.1			.4	.64	1.3
% A. S.	1.5		8.9	2.6			0.95	1.5	3.1

Plate Size 7 3/16"
Applied Stress 54.2 psi

Cell No.	10	16	15	12	6	22	13	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	.31		1.6	.46			.32	0.3	.66
% A. S.	0.5		2.9	.85			.52	0.6	1.2

TABLE 21

Field Pressure Cell Data

(-)12" Soil (+)8" Limestone

Series II

Plate Size 18"
Applied Stress 31.5 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth	12	12	12	12	12	12	12	12	12
Dist. ℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.	6.0	13.3	7.1		0.9	10.3	2.1	10.2	
% A. S.	19.0	42.4	22.6		2.7	32.6	6.7	32.2	

Plate Size 12"
Applied Stress 42.0 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth	12	12	12	12	12	12	12	12	12
Dist. ℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.	3.4	11.4	3.1		.46	7.1	.56	7.8	
% A. S.	8.0	27.0	7.4		1.1	16.8	1.3	18.5	

Plate Size 7 3/16"
Applied Stress 54.2 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth	12	12	12	12	12	12	12	12	12
Dist. ℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.	1.26	7.45	1.28		0.2	4.65	0.2	4.9	
% A. S.	2.3	13.7	2.4		0.4	8.6	0.4	9.0	

TABLE 21
(cont'd)

Field Pressure Cell Data

(-)12" Soil (+)8" Limestone

Series II

Plate Size 18"
Applied Stress 31.5 psi

Cell No.	10	16	15	12	6	22	13	19	23
Depth	20	20	20	20	20	32	32	32	32
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0.6		7.2	2.5	1.3	.23	1.0		2.7
% A. S.	1.9		23.0	8.0	4.1	0.7	3.2		8.6

Plate Size 12"
Applied Stress 42.0 psi

Cell No.	10	16	15	12	6	22	13	19	23
Depth	20	20	20	20	20	32	32	32	32
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	.35		4.8	0.9			0.43		1.53
% A. S.	0.8		11.5	2.1			1.0		3.6

Plate Size 7 3/16"
Applied Stress 54.2 psi

Cell No.	10	16	15	12	6	22	13	19	23
Depth	20	20	20	20	20	32	32	32	32
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0.3		2.1	0.4			0.2		0.7
% A. S.	0.6		3.9	0.74			0.4		1.35

TABLE 22

Field Pressure Cell Data

(-)12" Soil (+)12" Limestone

Series II
Aug. 28, 1958

Plate Size 18"
Applied Stress 31.5 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth	16	16	16	16	16	16	16	16	16
Dist. ℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.	1.33	10.1	6.3		1.5	8.0	2.2	8.5	
% A. S.	4.2	32.0	20.0		4.8	25.5	7.0	27.0	

Plate Size 12"
Applied Stress 42.0 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth	16	16	16	16	16	16	16	16	16
Dist. ℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.	3.2	8.4	3.0		0.7	1.4	1.0	6.5	
% A. S.	7.6	20.0	7.2		1.67	3.2	2.4	15.5	

Plate Size 7 3/16"
Applied Stress 68.2 psi

Cell No.	28	30	13	26	11	8	14	5	17
Depth	16	16	16	16	16	16	16	16	16
Dist. ℄	1.0	0	1.0	2.0	2.0	0.5	1.5	0.5	1.5
Meas. Str.	2.26	6.3	1.85		0.3	4.6	.33	4.15	
% A. S.	3.3	9.3	2.7		0.44	6.75	0.5	6.1	

TABLE 22
(cont'd)

Field Pressure Cell Data

(-)12" Soil (+)12" Limestone

Series II
Aug. 28, 1958

Plate Size 18"
Applied Stress 31.5 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0.87		5.1	0.6	1.3	0.13	0.8		2.2
% A. S.	2.7		16.1	1.9	4.2	0.4	2.5		7.0

Plate Size 12"
Applied Stress 42.0 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0.6		3.3	1.1	0	0	0.5		1.5
% A. S.	1.4		7.9	2.6			1.2		3.6

Plate Size 7 3/16"
Applied Stress 68.2 psi

Cell No.	10	16	15	12	6	22	18	19	23
Depth	24	24	24	24	24	36	36	36	36
Dist. ℄	2.0	1.0	0	1.5	2.5	3.0	2.0	1.0	0
Meas. Str.	0.15		2.16	0.54	0	0	0.32		0.88
% A. S.	0.23		3.16	0.8	0	0	0.47		1.29

TABLE 23

Field Subgrade and Base Course Data

Soil Data

Series I

					Triaxial E	Load Test E
Top 4"	γ_w = 119.6	w = 26.3	γ = 95.3	% Sat. 92.0	450	405
2nd 4"	122.0	24.0	98.3		470	530
3rd 4"	119.1	28.2	93.0			575
4th 4"	122.0	26.2	96.5		460	

L.L. 44.5 P.L. 23.6 P.I. 20.9

Series II

					Triaxial E	Load Test E
Top 6"	121.5	24.6	97.5		650	740
Bot.6"	122.2	25.0	98.0		1000	820

L.L. 36.1 P.L. 22.4 P.I. 14.4

Note: The P.I. of this soil changes with original moisture content.

Optimum Moisture Content - 18.0 Proctor Density 105.0

Base Material

Crushed Limestone Indiana Highway Commission Type K

Avg. Moisture Content 3.5% Avg. Density 129.5 psi

Shear Strength - Triaxial Test at A Density of 138.6 psi

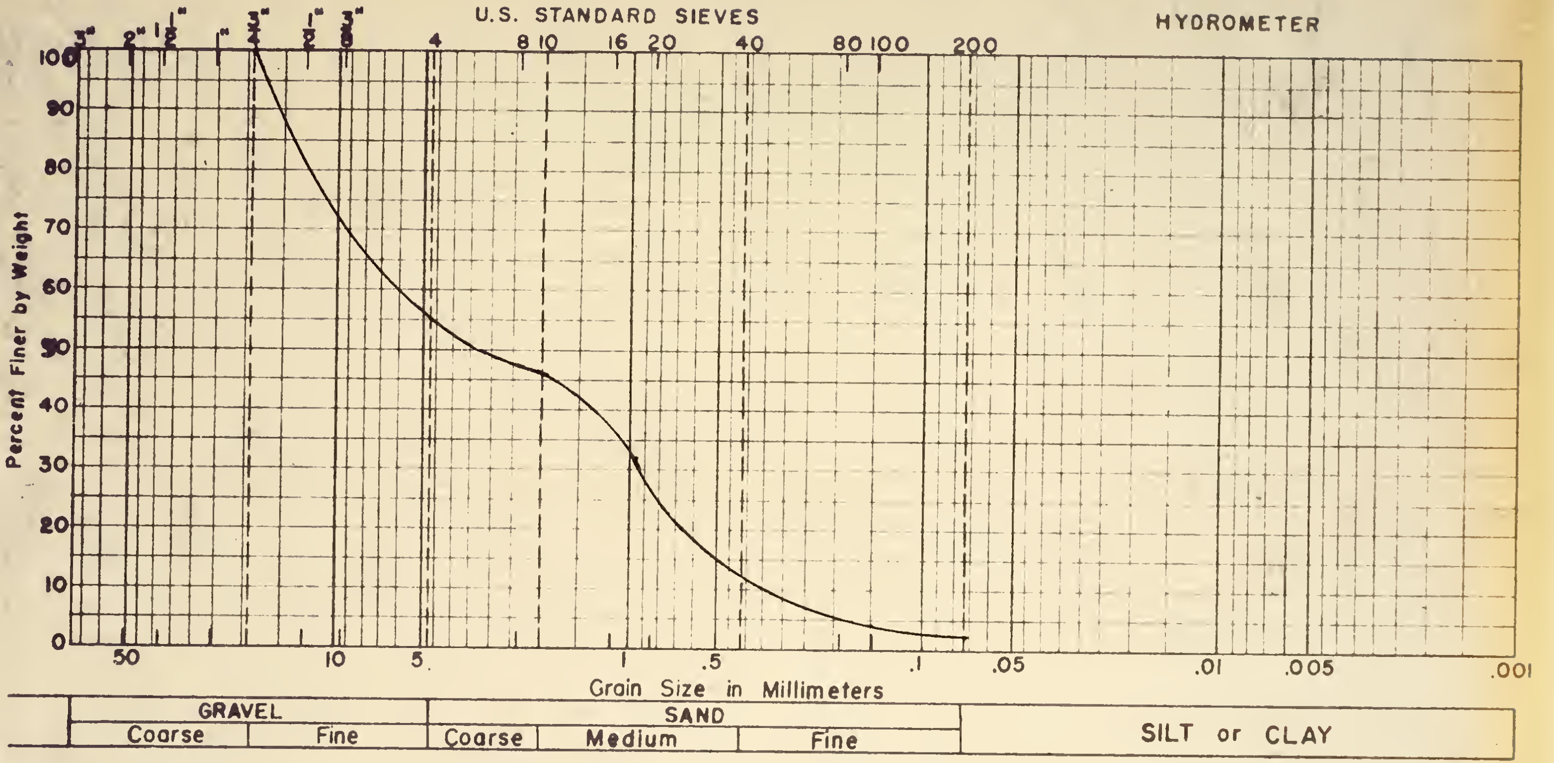
ϕ = 48.0 C = 7.0 psi

TABLE 24

Computed Values of "E" from Load Test

Aggregate Cover

Cover		Series	Calculated E Values		
Base Thickness	Soil Removed		18" Plate	12" Plate	7-3/16" Plate
+4	-4	I	457	600	710
+4	-8	I	560	780	903
+4	-12	I	795	905	1120
+4	-4	II	1065	960	1110
+4	-8	II	1180	990	1015
+4	-12	II	1200		
+4	-4	I	390	427	
+8	-8	I	1060	1250	1200
+8	-12	I	1580	1570	1830
+8	-8	II	1680	2130	2450



Remarks

GRAIN SIZE DISTRIBUTION
BASE COURSE MATERIAL
FIGURE 47

APPENDIX D

TABLE 25

Comparison of Measured Stresses

Below Center of Plate
Soil Only

Corps of Engineers Data				McMahon Data					
r = 17.81" 60,000 lb. load 60 psi				r = 9.0		r = 6.0		r = 3.59	
Depth feet	Stress psi	Z/r	% A.S.	Z/r	% A.S.	Z/r	%A.S.	Z/r	% A.S.
1.0	56.1	.675	93.5	.75	91.5		87.0		
2.0	30.7	1.35	52.0	1.0	79.0		77.0		
3.0	18.9	2.03	31.6	1.5	52.0		56.0		55.0
4.0	11.4	2.70	19.1	2.0	31.0		37.0		38.0
5.0	8.9	3.37	14.8	2.5					27.0
				3.0	15.0		17.0		18.0
				4.0	8.0		9.0		8.0

TABLE 26

Calculations for Equivalent Plate Method

18" Plate   4" Aggregate Cover

Assumed intersection with the base at 73.0%

$254 : 73 :: x : 100 \rightarrow x = 348$ sq. in.

$18^2 : 254 :: D^2 : 348 \rightarrow D^2 = 444 \quad D = 21.1$

Data for Theoretical Curve r = 10.55

Z/r	Depth Inches	Equivalent Depth	% Applied Stress	Equivalent % Applied Stress
0.25	2.63	6.63	98	71.3
0.5	5.25	9.25	90	66.7
.75	7.88	11.88	80	58.3
1.0	10.55	14.55	65	43.3
1.25	13.18	17.18	50	36.5
1.5	15.80	19.80	43	31.4
2.0	21.1	25.1	28	20.4
3.0	31.65	35.65	14.5	10.6

TABLE 27

Calculations for Equivalent Plate Method

12" Plate   4" Aggregate Cover

Assumed intersection with base at 54.0%

113: 53 :: x : 100 → x = 209 sq. in.

12^2: 113:: D^2: 209 → D^2= 266 D = 16.3

Data for Theoretical Curve r = 8.15

z/r	Depth Inches	Equivalent Depth	% Applied Stress	Equivalent % Applied Stress
0.25	2.03	6.08	98	53.0
0.5	4.10	8.10	90	49.0
0.75	6.13	10.13	80	43.2
1.0	8.15	12.15	65	35.3
1.5	12.25	16.25	43	23.3
2.0	16.35	20.35	28	15.2
2.5	20.45	24.45	20	10.8
3.0	24.45	28.45	14.5	7.8
4.0	32.60	36.60	8.7	4.7

TABLE 28

Calculations for Equivalent Plate Method

7 3/16" Plate   4" Aggregate Cover

Assumed intersection with base at 36.0%

40.6 : 36 :: x : 100 → x = 113

7.18^2: 40.6:: D^2: 113   D = 12.0"

Data for Theoretical Curve r = 6.0"

Z/r	Depth Inches	Equivalent Depth	% Applied Stress	Equivalent % Applied Stress
0.5	3.0	7.0	90	32.4
1.0	6.0	10.0	65	23.4
1.5	9.0	13.0	43	15.5
2.0	12.0	16.0	28	10.1
2.5	15.0	19.0	20	7.2
3.0	18.0	22.0	14.5	5.2
4.0	24.0	28.0	8.7	3.14
5.0	30.0	34.0		

TABLE 29

Calculations for Equivalent Plate Method

18" Plate   8" Aggregate Cover

Assumed intersection with base at 38.0%

$254 : 38 :: x : 100 \rightarrow x = 670$ sq. in.

$18^2 : 254 :: D^2 : 670 \rightarrow D^2 = 855 \quad D = 29.2$

Data for Theoretical Curve   r = 14.6

z/r	Depth Inches	Equivalent Depth	% Applied Stress	Equivalent % Applied Stress
.25	3.6	11.6	98	37.2
.50	7.3	15.3	90	34.2
.75	10.9	18.9	80	30.4
1.0	14.6	22.6	65	24.6
1.5	21.9	29.9	43	16.2
2.0	29.2	37.2	28	10.6

TABLE 30

Calculations for Equivalent Plate Method

12" Plate   8" Aggregate Cover

Assumed intersection with base at 28.0%

113 : 28 :: x : 100 = 404 sq. in.

$12^2 : 113 :: D^2 = 404 \rightarrow D^2 = 512 \quad D = 22.6$

Data for Theoretical Curve r = 11.3

Z/r	Depth Inches	Equivalent Depth	% Applied Stress	Equivalent % Applied Stress
.25	2.8	10.8	98	27.5
.5	5.6	13.6	90	25.0
.75	8.4	16.4	80	22.4
1.0	11.3	19.3	65	18.2
1.5	16.9	24.9	43	12.0
2.0	23.2	31.2	28	7.8

TABLE 31

Calculations for Equivalent Plate Method

7 3/16" Plate   8" Aggregate Cover

Assumed intersection with base at 14.0%

$40.6 : 14 :: x : 100 \rightarrow x = 290$

$7.2^2 : 40.6 :: D^2 : 290 \rightarrow D^2\ 370 \quad D = 19.2"$

Data for Theoretical Curve r = 9.6

Z/r	Depth Inches	Equivalent Depth	% Applied Stress	Equivalent % Applied Stress
.25	2.4	10.4	98	13.7
.5	4.8	12.8	90	12.6
.75	7.2	15.2	80	11.1
1.0	9.6	17.6	65	9.1
1.5	14.4	22.4	43	6.0
2.0	19.2	27.2	28	3.9
2.5	24.0	32.0	20	2.8
3.0	28.8	36.8	14.5	2.0

SAMPLE CALCULATIONS

Calculation of Values for Burmister Comparison

For rigid bearing area $E_2 = \frac{1.18\ p_2 r}{w}$ and $F_w = \frac{wE_2}{1.18\ p_1 r}$

18" plate on subgrade @ -4"   Series I

$$E_2 = \frac{1.18 \times 2650/254 \times 9}{0.2} = 550$$

Top 4" base

$$F_w = \frac{0.2 \times 550}{1.18 \times 2450/254 \times 9} = 1.05 \rightarrow E_2/E_1 = 1/1$$

18" plate on subgrade @ -8"   Series I

$$E_2 = \frac{1.18 \times 9 \times 52.7}{0.2} = 666$$

Top 8" base

$$F_w = \frac{0.2 \times 666}{1.18 \times 4750/254 \times 9} = .666 \quad h/r = 8/9 = .89 \rightarrow E_2/E_1 = 1/4$$

18" plate on subgrade @ -4"   Series II

base +4"

$$E_2 = 930$$

$$F_w = \frac{0.2 \times 930}{1.18 \times 9 \times 22.9} = 0.78 \quad h/r = 4/9 = .45 \rightarrow E_2/E_1 = 1/10$$

18" plate on subgrade @ -8"   Series II

base + 8"

$$E_2 = 930$$

$$F_w = \frac{0.2 \times 930}{1.18 \times 9 \times 35.7} = .490 \quad h/r = .89 \rightarrow E_2/E_1 = 1/14$$

VITA

VITA

Thurmul Francis Mc Mahon was born in Beattie, Kansas, on April 23, 1912. He attended the Beattie Public Schools, graduating from High School in 1929. He attended St. Benedict's College, Atchison, Kansas, and Kansas State College, Manhattan, Kansas.

Mr. Mc Mahon was employed as a Soil Technician by the Works Progress Administration in 1936 and 1937. He was in charge of the control of the placement of earth fill in Earth Fill dams. In 1939, Mr. Mc Mahon moved to California where he worked as a plumber and later as a rodman on a survey party for the City of Los Angeles.

In 1942 he was drafted into the Army of the United States. He was sent to Officers Candidate School at Fort Belvoir and was commissioned a Second Lieutenant. Lt. Mc Mahon was assigned to the 969th Engineering Maintenance Company at Plattsburg, New York, as Platoon Commander. While there he met and was married to Miss Helen Williams of Peekskill, New York. Lt. Mc Mahon was in the European Theatre for eighteen months. His last Army assignment was Engineer Maintenance Officer of the Berlin District.

In 1946 he entered Columbia University in New York City, where he finished his work for a BSCE at Kansas State College and a MSCE from Columbia in 1948. He accepted a position at the University of Kansas as Assistant Professor of Civil Engineering, in charge of the Soil Mechanics and Highway Engineering program. He acquired his present rank of Associate Professor in 1958.

Mr. Mc Mahon holds membership in the American Society of Civil Engineers, American Society for Engineering Education, National Society of Soil Mechanics and Foundation Engineering, Committee D-18 of the American Society for Testing Materials, Sigma Xi, Sigma Tau, and Tau Beta Pi. He serves as the Kansas University contact member of the Highway Research Board. He is a registered Professional Engineer in the State of Kansas.